

Impact of thruster body electrical configuration on Hall effect discharge impedance characteristics

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ABSTRACT

This paper investigates how grounded, floating, and cathode-tied thruster body electrical configurations affect current pathways in a vacuum test facility and the Hall effect thruster discharge impedance from 100 Hz to 300 kHz. A current pathways model is extended to include the thruster body pathway and is used to interpret witness-plate ion and electron current measurements, discharge telemetry, and small signal impedance measurements. The witness-plate measurements reveal configuration-dependent changes in far-field electron collection. The cathode-tied configuration produces the highest electron saturation currents at nearly all measurement locations, whereas the grounded configuration produces the lowest values at nearly all background plasma locations. The impedance measurements similarly reveal configuration-dependent resistance and reactance. Near the dominant breathing mode frequency, the grounded configuration exhibits an impedance magnitude about 30% higher than those of the other configurations and a positive to negative phase transition near the first impedance peak. The grounded configuration also produces discharge-current peak-to-peak oscillations approximately 16% larger than those measured in the other configurations. Its reactive response is consistent with a possible contribution from plasma sheath capacitance, although this contribution cannot be independently separated from other reactive effects associated with the implemented electrical configuration. Together, these results demonstrate that the conductive thruster body functions as an electrical boundary condition that influences the effective discharge load impedance and the distribution of far-field electron current pathways.

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I. INTRODUCTION

In recent years, space missions have implemented Hall effect thrusters (HETs) as the primary in-space propulsion technology. HETs ionize a propellant and, using crossed magnetic and electric fields, accelerate the resulting ions to produce thrust. The high ion exhaust velocities achieved yield specific impulse values on the order of several thousand seconds, making HETs an attractive option for long-duration missions. Performance and lifetime quantification of HETs rely on ground-based test environments designed to replicate the space environment. Investigating the inherent differences between these environments and their effects

on HET performance and stability remains an active area of research within the electric propulsion community.

The discrepancy between ground-based testing environments and in-space HET characterization has been previously reported in the literature. One of the earliest examples dates back to the SMART-1 mission, where it was observed that the PPS-1350-G HET yielded lower *I_{sp}* values and smaller discharge current oscillation frequencies than those measured during ground tests.¹ More recently, the H2Sat mission indicated a decrease in the maximum ion energy peak compared to ground measurements from an RPA at the same spatial position relative to the SPT-100 HET.²

These discrepancies are often attributed to differences between the test and space environments and are commonly referred to as facility effects. Facility effects arise from variations in how a HET interacts with the ground environment compared to the space environment, ultimately leading to differences in performance and stability. These effects are typically categorized as follows: (1) pressure, (2) contamination, and (3) electrical. The focus of this paper is on electrical facility effects.

Electrical facility effects are created by the electrical interactions between the thruster discharge and (1) the conductive facility walls and (2) the thruster body. In space, beam ions that originate in the HET discharge recombine with electrons emitted from the cathode, many meters downstream of the HET exit plane. In a ground-based test facility, however, beam ions may also recombine with electrons from other sources, such as those associated with the conductive facility walls and the thruster body. As a result, the recombination pathways present during ground testing differ from those in the space environment. Furthermore, the conductive facility walls and thruster body impose electrical boundary conditions that the plasma must satisfy. Typically, the facility walls are grounded, while the thruster body may be electrically tied to cathode common, grounded, or electrically floating. These boundary conditions modify the electrical interactions between the thruster, the plasma, and the surrounding environment, i.e., influencing the mechanisms that maintain the conservation of current and sustain a quasi-neutral plasma. Variations in these physical processes can affect a thruster's stability, performance, and lifetime. The associated discharge current oscillations are also important to HET-PPU integration. In particular, the PPU discharge supply and output filter must accommodate the thruster's current oscillations, while harness impedance can generate appreciable voltage ripple at the thruster.^{3,4}

The objective of this paper is to investigate how the primary thruster body electrical configurations, grounded, floating, and cathode tied, affect ion and electron current pathways and, therefore, the HET impedance profile between the frequency band of 100 Hz and 300 kHz. To achieve this objective, we present an updated current pathways model that captures the thruster body current pathway. Next, we quantify the ion and electron currents near the facility walls for each configuration to demonstrate the extent of the impact the thruster body electrical configuration has on current pathways. Finally, we relate these changes in ion and electron currents to the corresponding changes in the impedance profile. The electron current measurements will confirm that preferential electron current pathways exist depending on the thruster body electrical configuration. Additionally, the measurement locations will demonstrate how a near-field electrical boundary condition, specifically the thruster body, influences the far-field plasma environment and the magnitude of this effect. Time-varying thruster discharge current waveforms are also analyzed to explain why the grounded thruster body electrical configuration appears to be the least stable operating state. Stability is defined here by the discharge current peak-to-peak value, which is highest in this configuration across both this study and prior thruster body studies.

The paper is organized as follows. Section II presents the electrical boundary conditions imposed by each thruster body

electrical configuration and the resulting distinct current pathways. Section III provides an overview of the experiment, including the vacuum test facility, thruster, and diagnostics used. Section IV presents thruster telemetry, ion current density measurements from Faraday sweeps, ion and electron saturation current measurements near the facility walls, and impedance profiles. Section V presents the impact of thruster body electrical configuration on HET dynamics through thruster operating parameters, with an emphasis on discharge current peak-to-peak values. The impact on ion and electron current pathways is then discussed and related to the current pathways model presented in Sec. II. The resulting pathway changes are used to explain the resistance and reactance plots extracted from the impedance profiles. These plots are compared across thruster body electrical configurations to quantify how the thruster body influences the dynamic behavior of a HET through resistive, inductive, and capacitive effects. We conclude by emphasizing that the thruster body introduces a capacitive effect through the plasma thruster body sheath, causing it to act as a near-field electrical boundary condition. Through its influence on electron current pathways and discharge impedance behavior, this boundary condition can strongly affect far-field plasma behavior and overall discharge stability. These results emphasize the importance of accounting for thruster body electrical configuration when interpreting HET behavior in ground-based vacuum test facilities.

II. BACKGROUND

A. Thruster body electrical configurations

The thruster body is defined as the support structure, typically conductive, by which the HET is fastened to the spacecraft chassis. The nearest surface at the thruster body potential relative to the discharge channel varies across HETs. Depending on the thruster design, the inner and outer front pole covers may be either conductive surfaces electrically connected to the thruster body or dielectric surfaces electrically isolated from it. Commercial and industry supported Hall-thruster test campaigns have employed multiple thruster body electrical configurations. The Aerojet Rocketdyne XR-5, SITAEL HT20k DM2, and Busek BHT-7000 were tested with their thruster bodies connected to the facility ground, whereas the IHI Aerospace/Mitsubishi Electric 6-kW subsystem was tested with its thruster body connected to cathode common.^{5,6} In a separate Busek-supported campaign, the experimental Diverging Cusped-Field Hall Thruster operated with its body electrically floating.⁷ Figure 1 shows a schematic of each configuration. In the floating configuration, the dashed line represents AC current between the near-field plasma and the exposed conductive thruster body.

B. Previous work

There is limited research on electrical facility effects, and the work that has been conducted focuses primarily on the electrical interactions between the thruster discharge and conductive facility walls. Walker *et al.* measured currents collected by aluminum plates electrically tied to ground and positioned 4.3 m axially and 2.3 m radially from the thruster exit plane.⁸ These measured

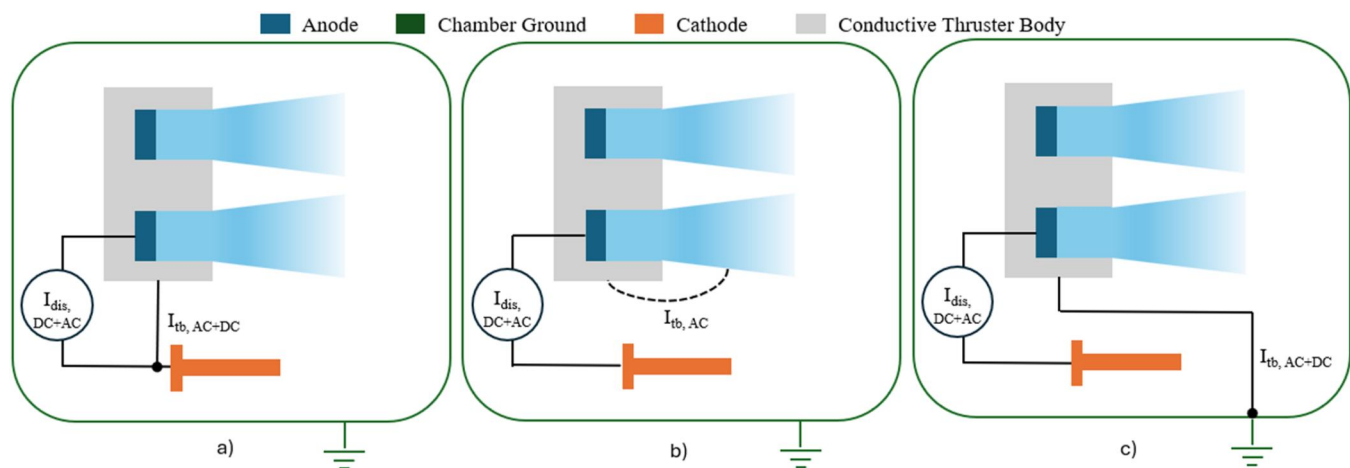


FIG. 1. Thruster body electrical configurations: (a) tied to cathode common, (b) floating, and (c) grounded.

currents were 13.6% and 10.7% of the discharge current. The results indicated that the conductive facility walls serve as a recombination current pathway. Walker's later work focused on the impact of cathode position relative to the thruster centerline. Using the same aluminum plates, current measurements on nearby conductive surfaces increased as the cathode was moved away from the thruster centerline, indicating changes in current pathways due to cathode position.⁹ He also investigated the effect of varying the thruster body electrical configuration from floating to grounded, which resulted in approximately 25% of the discharge current being sunk, indicating that the thruster body provides a substantial current pathway during HET operation in grounded facilities.¹⁰

Peterson *et al.* performed performance, plume, and stability studies on the following thruster body electrical configurations: (1) grounded, (2) floating, and (3) cathode tied.¹¹ Each configuration was tested with both conductive and dielectric front pole covers. The grounded configuration produced the highest thrust among the thruster body electrical configurations. However, ion current density measurements at constant discharge power remained similar, indicating that the overall plume characteristics were relatively insensitive to the thruster body electrical configuration. Time-varying discharge current measurements also showed that the grounded configuration was the most oscillatory, with a peak-to-peak discharge current approximately 90% of the mean discharge current.

Huang *et al.* subsequently used laser-induced fluorescence to investigate the effects of electrical configuration on the ion velocity field of the HERMeS TDU-1 Hall thruster.¹² The axial acceleration profile was largely unchanged between the cathode-tied and facility grounded configurations, while floating the thruster body produced a slight upstream shift of the acceleration zone. The ion characteristics measured near the front pole covers were also largely insensitive to electrical configuration. Together, these results show that thruster-body electrical configuration can affect performance and discharge oscillations without producing

comparably large changes in the bulk ion-acceleration characteristics. This observation motivates examining changes in electrical coupling and current pathways as potential contributors to the configuration-dependent discharge behavior.

Previous HET studies involving impedance have primarily examined the influence of harness and power supply impedance on discharge oscillations. Pinero used electrical measurements and SPICE modeling to show that discharge-current oscillations interacting with the harness impedance can generate appreciable voltage ripple at the thruster.⁴ Brieda *et al.* subsequently incorporated finite harness and power-supply impedance into a physics-based HET model to investigate their influence on the oscillatory behavior of the discharge.¹³ More recently, Jovel *et al.* applied small-signal impedance analysis to an operating HET and identified frequency-dependent resistive, inductive, capacitive, and resonant characteristics in the impedance profile of the HET discharge.¹⁴ Impedance based techniques have also been applied to other plasma systems. Lee *et al.* used impedance measurements in an inductively coupled plasma reactor and characterized contributions from the transmission line and surrounding structural components to isolate the plasma response.¹⁵ Myra *et al.* experimentally measured and modeled the frequency-dependent sheath impedance in a large magnetized plasma, demonstrating that plasma sheaths can exhibit measurable resistive and reactive behavior.¹⁶ Collectively, these studies demonstrate the broader application of impedance-based techniques for characterizing the frequency-dependent electrical response of plasma discharges and plasma sheaths.

In the complementary work, Jovel developed an equivalent current pathways model that captures the electrical coupling between the HET discharge and the ground-based vacuum test facility.¹⁷ The model provides an approach for understanding how the various current pathways present during ground testing affect the HET discharge circuit, specifically those involving the conductive facility walls. Resistors, inductors, and capacitors in each current pathway indicate physical plasma processes, expressed as

an effective impedance, that govern the overall discharge load. One of the primary findings of this work is that the conductive facility walls induce a capacitive effect, storing charge across the plasma-facility wall boundary. This capacitive behavior may help account for differences in HET stability observed between ground and on-orbit operation.

However, previous studies have not examined how changes in thruster-body electrical configuration affect both facility current pathways and the impedance profile of the HET discharge under otherwise similar operating conditions. To address this gap, the following extends Jovel's current pathways model to include the thruster-body current pathway and the electrical boundary condition imposed by each of the three thruster body configurations.

C. Impact of thruster body electrical configuration on HET discharge-facility current pathways

Electrical boundary conditions impact current pathways in vacuum test facilities because they define the constraints that the local plasma environment must satisfy. The thruster body acts as an additional conductive surface, similar to facility walls, that imposes an electrical boundary condition on the local plasma. However, its proximity to the HET is much closer than that of the facility walls. There is currently no consensus within the community on the precise definition of the near-field vs far-field plasma regions, although a distance of approximately 1 m is often assumed. Using this reference, the thruster body surface is several orders of magnitude closer than the typical boundary between the near-field and far-field regions. Previous studies have shown that modifying far field electrical boundary conditions using a biased electrode does not significantly affect near-field current pathways, while far-field electron current pathways near the facility walls are affected.¹⁴ Studies examining near-field electrical boundary conditions, specifically those associated with the thruster body, have not been performed. Therefore, the extent to which the thruster body boundary condition influences current pathways is poorly understood.

Each thruster body electrical configuration presents a unique electrical boundary condition. The grounded configuration creates a near-field current pathway to ground, allowing nearby electrons to sink to ground and replenish electrons at the facility walls that participate in recombination events. In this way, the thruster body behaves as an extension of the chamber. The floating configuration imposes a net-zero current boundary condition over its surface area. That is, the ion and electron flux across the thruster body surface must be equal. The cathode-tied configuration establishes a current pathway between the thruster body, which contains its own available electrons, and the electrons emitted by the cathode. Depending on the configuration selected, preferential current pathways may exist and, therefore, result in different HET dynamics.

Changes in current pathways may influence the HET's discharge load impedance profile. The HET discharge behaves as a complex electrical load governed by physical processes occurring throughout the plasma environment. Each of these processes can be represented using electrical engineering elements such as resistors, inductors, and capacitors to help explain their contributions

to the overall discharge HET impedance. For example, if there is a preferential current pathway, as indicated by an increase in current, the underlying physical process should be represented by a corresponding decrease in impedance within the equivalent circuit model. Leveraging the existing current pathways model that captures the electrical coupling between the HET discharge and the ground-based vacuum test facility, the model was expanded to include the current pathway between the discharge and the thruster body. Each configuration presents unique current pathways, which are shown separately in Figs. 2–4. The resistive, inductive, and capacitive elements in the current pathways model represent effective impedances associated with the physical plasma processes governing each pathway. In its present form, the model focuses on these plasma-mediated processes and does not independently resolve all parasitic circuit contributions associated with the experimental configuration. Future development of the model will incorporate a more comprehensive treatment of independently characterized parasitic impedances.

The grounded, floating, and cathode-tied current pathways models are shown in Figs. 2–4, respectively. The effect of the thruster body electrical configuration on the discharge impedance can be modeled using an effective plasma-thruster body sheath capacitance. The plasma sheath forms over the thruster body to meet the potential boundary conditions set by the local plasma environment and the thruster body with respect to ground. If the electrical configuration of the thruster body varies, then the sheath formed over the body will vary to meet that new potential boundary condition. The sheath capacitance derived by Chen can be used to model the interface between the two regions.¹⁸ The resulting plasma-thruster body RC element represents an effective sheath response to both ion and electron fluxes at the thruster body surface. Although the element is drawn along the thruster body CEX-ion pathway in Figs. 2–4, it is not intended to represent an ion-specific sheath. This change in sheath formation over the HET body influences both the sheath's capacitive, $C_{sh,CEX,tb}$, and resistive, $R_{sh,tb}$, effects on the overall discharge load. Depending on the thruster body's electrical configuration, the associated current pathway exhibits different impedance values, thereby influencing local CEX ion and cathode electron populations and impacting the remaining discharge facility current pathways.

For the grounded configuration shown in Fig. 2, CEX ions collected by the thruster body recombine locally at the thruster body surface. The thruster body and chamber wall are maintained at the same electrical potential through facility ground and are therefore part of the same grounded conductive structure, although their respective plasma-facing sheath interfaces remain spatially distinct. Electron current from cathode electrons may also be collected by the grounded thruster body and contribute to recombination at the thruster body surface. To explicitly represent this pathway, Fig. 2 includes an equivalent electron representation of the plasma thruster-body sheath. This element represents the same physical sheath shown on the thruster-body CEX ion pathway and does not indicate an additional sheath.

For the floating configuration shown in Fig. 3, the thruster body is electrically isolated from all other conductive surfaces. Consequently, the net DC current to the floating thruster body must approach zero, while AC current may still be exchanged

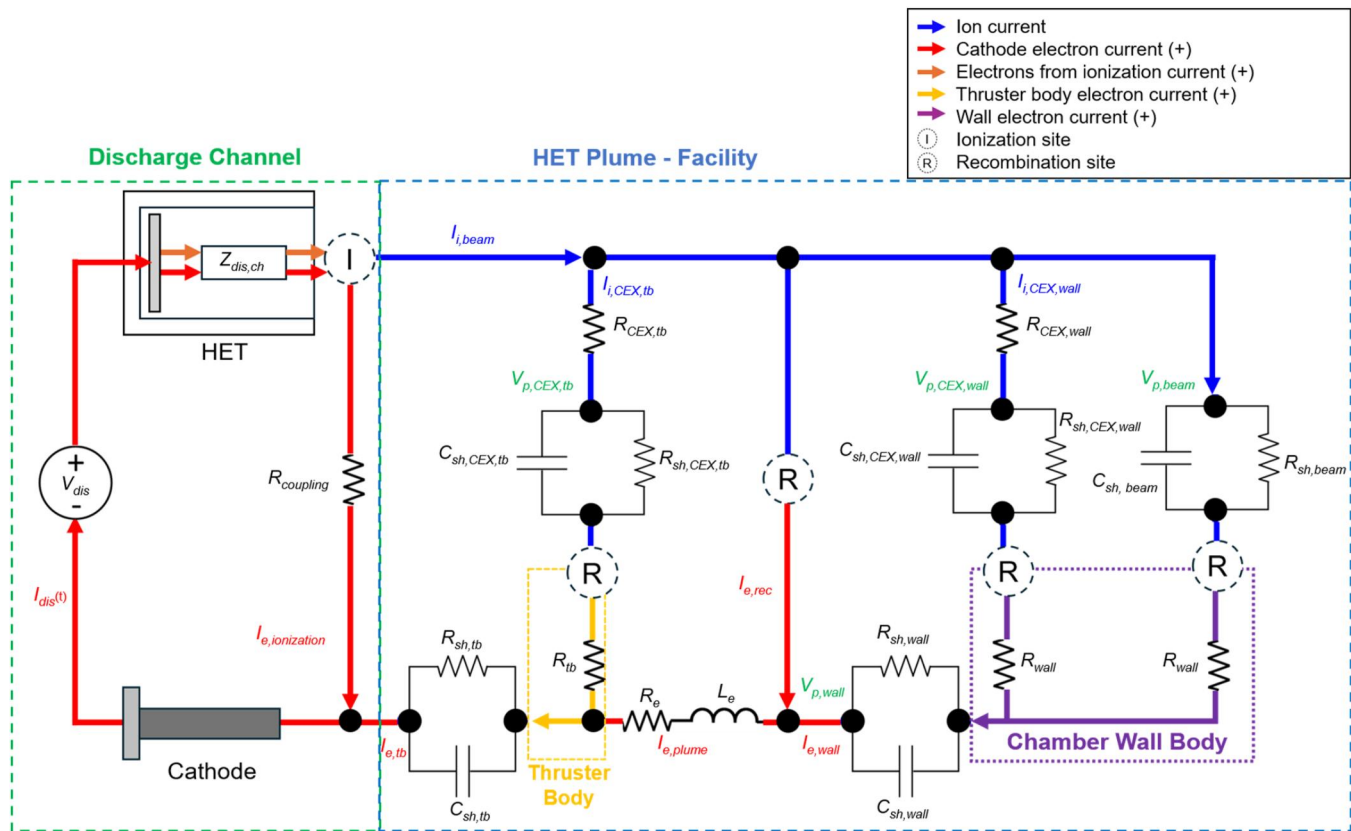


FIG. 2. HET discharge-facility current pathways model with a grounded thruster body electrical configuration.

between the local plasma and the thruster body. The plasma thruster body RC element therefore represents the effective sheath response to both ion and electron fluxes at the thruster body surface as the thruster body potential adjusts to satisfy this condition. A separate electron representation is not shown because the single RC element represents the same physical plasma thruster body sheath for both species.

For the cathode-tied configuration shown in Fig. 4, the thruster body is maintained at the cathode common potential. The plasma–thruster body sheath remains present at the plasma-facing thruster body surface and governs the local collection of ions and electrons, while the electrical connection to cathode common provides an additional pathway for current through the thruster structure. As in the floating configuration, the single plasma–thruster body RC element represents the effective sheath response to both ion and electron fluxes at the thruster body surface and a separate electron representation is not shown for clarity.

III. EXPERIMENT OVERVIEW

The test campaign was conducted at the Georgia Institute of Technology's High Power Electric Propulsion Laboratory in Vacuum Test Facility 2 (VTF-2). This section describes the

thruster, vacuum test facility, and diagnostics used in the experiment.

A. Test article

The H9 HET was used in this experiment at the 300 V, 15 A thruster operating condition. It was developed by the University of Michigan, the Air Force Research Laboratory, and the Jet Propulsion Laboratory.¹⁹ The H9 uses a center-mounted lanthanum hexaboride hollow cathode. The thruster body electrical configurations examined in this test campaign are (1) grounded, (2) floating, and (3) tied to the cathode common. The H9 HET was operated on krypton at constant discharge current across each thruster body electrical configuration. The H9 employs graphite inner and outer front pole covers that are electrically connected to the thruster body and are therefore maintained at the thruster-body potential. The thruster body was electrically isolated from the facility after installation on the thrust stand using grade L5 ceramic standoffs located between the thruster mounting brackets and the thrust-stand pedestal. The thruster body and mounting brackets were maintained at the same electrical potential, whereas the thrust-stand pedestal and surrounding conductive facility structures remained tied to facility ground. Therefore, the

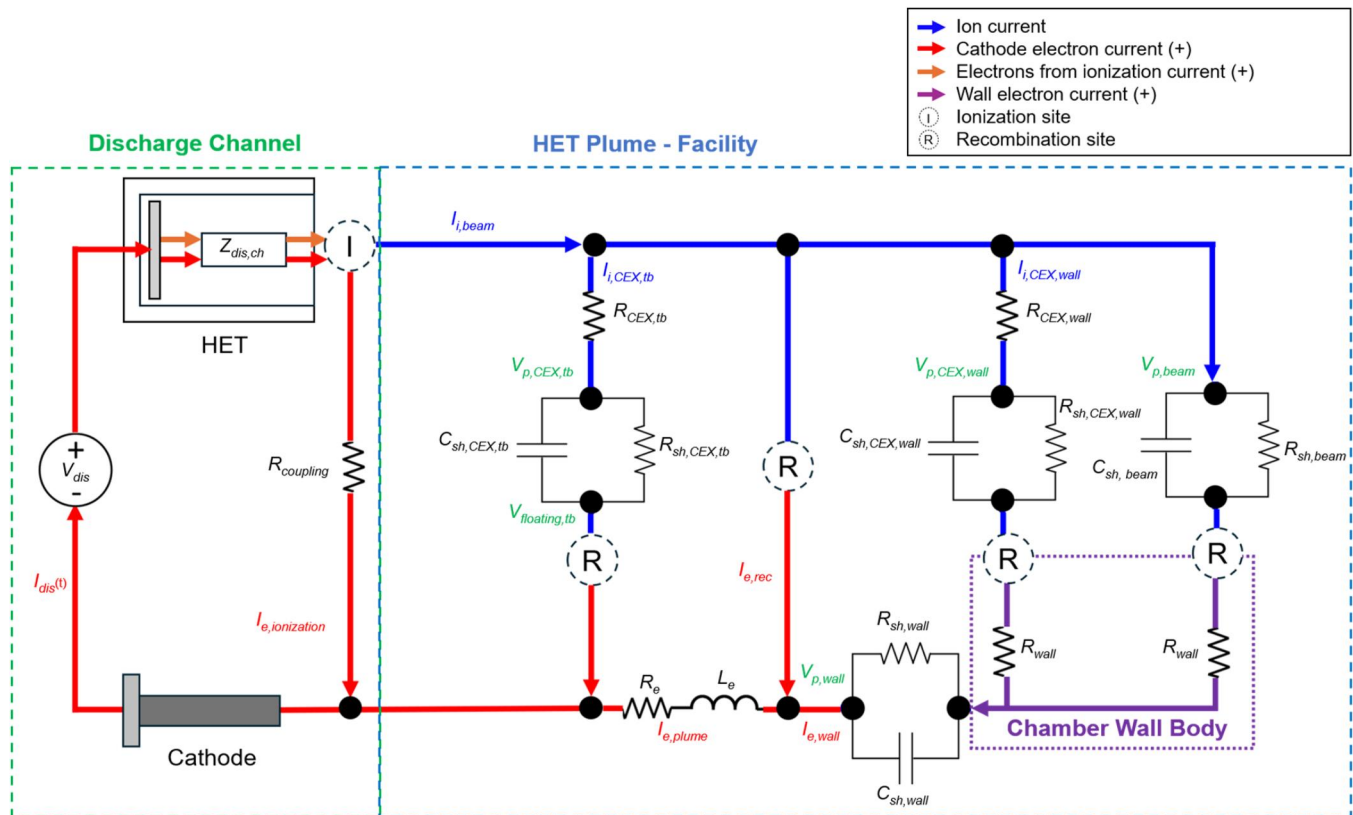


FIG. 3. HET discharge-facility current pathways model with a floating thruster body electrical configuration.

mounting brackets are considered part of the thruster body in this study. Electrical isolation was verified using the MEGGER 525 high potential tester at 250 V, which yielded a resistance of 5.4 GΩ. An unpaired 6-AWG stranded wire, approximately 118 ft long, was fastened to the thruster body and routed to the electrical breakout box inside VTF-2's control room. The thruster body-to-ground potential was measured using a Fluke 87 V multimeter.

A 50-kW DC power supply manufactured by Magna-Power was used to sustain the thruster discharge. The switching frequencies of the power supply are 600 Hz and 57.6 kHz. The anode and cathode discharge leads were each approximately 118 ft long and consisted of 6-AWG stranded wire. To protect the discharge power supply, an RC filter consisting of a 0.53-Ω resistor and a 100-μF capacitor was placed between the power supply and thruster discharge power lines. A Teledyne LeCroy HDO6104 oscilloscope was used to take time-varying discharge current, discharge voltage, and cathode-to-ground potential waveform traces. A Teledyne LeCroy CP150 current probe with a bandwidth of 10 MHz was used to measure the discharge current. It was placed on the low side of the discharge circuit, between the chamber power feedthrough and RC filter. In the cathode-tied configuration, the probe was located electrically outside the body-to-cathode

junction and therefore measured the net current after the cathode and thruster body current pathways recombined. The current through the body-to-cathode connection was not measured separately. The discharge voltage was measured using a Powertek DP25 high-voltage differential probe with a bandwidth of 25 MHz at the chamber power feedthrough. The discharge current, discharge voltage, and cathode-to-ground potential measurements were recorded simultaneously at a sampling frequency of 10 MS/s over a 100 ms measurement window. Additionally, two MKS GE50A mass flow controllers with 1% uncertainty were used to set the mass flow rates of the anode and the cathode that has a flow fraction of 7%. The average anode flow rate was 11.46 mg/s for the floating configuration, 11.34 mg/s for the cathode-tied configuration, and 11.25 mg/s for the grounded configuration.

B. Vacuum test facility

Experiments were conducted at the Georgia Institute of Technology's High-Power Electric Propulsion Laboratory in Vacuum Test Facility 2. The stainless-steel chamber measures 4.9 m in diameter by 9.2 m in length. Low base pressures of 2×10^{-8} Torr-N₂ are achieved via ten liquid nitrogen cooled PHPK TMI1200i cryopumps that provide a nominal pumping

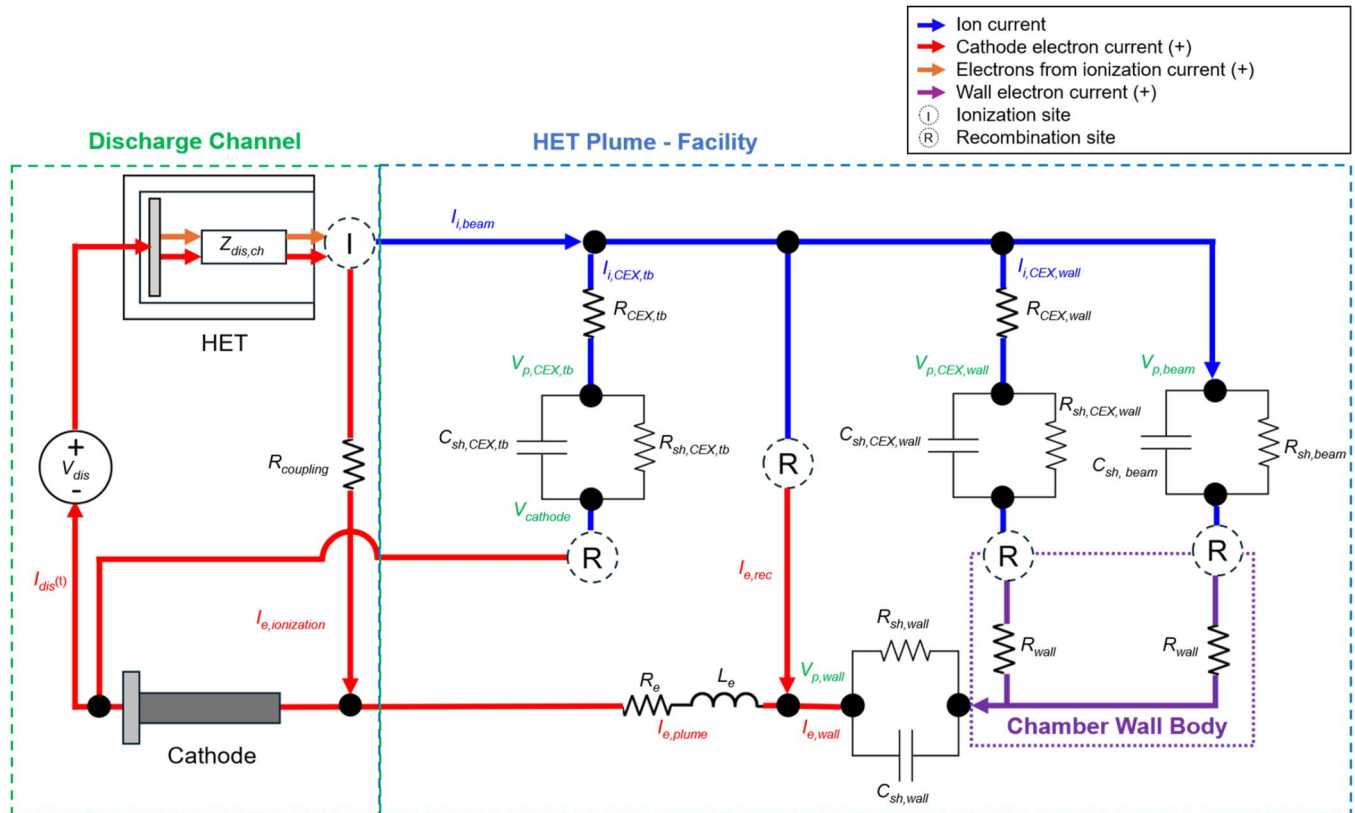


FIG. 4. HET discharge-facility current pathways model with a cathode-tied thruster body electrical configuration.

speed of 350 k/s on xenon. The facility features a closed-loop, liquid nitrogen liquefaction system.

A Varian 571 Bayard-Alpert hot filament ion gauge was used to measure the facility pressure 1 m away from the thruster exit plane. The ion gauge was mounted vertically, with a neutralizer attached directly to the gauge inlet. The neutralizer opening was oriented perpendicular to the anode flow direction, thereby eliminating a direct line of sight between the thruster plume and the gauge filament, consistent with recommended practices for pressure measurements during electric-propulsion testing.²⁰ The pressure measurements were displayed by an Agilent XGS-600 controller and recorded using LabVIEW software. The facility operating pressure remained below 5.4×10^{-6} Torr-Kr.

C. Witness plates and Faraday probe

To quantify differences in current pathways as the thruster body electrical configuration varies, witness plates were used as diagnostics to measure ion and electron saturation currents. An array of 28 witness plates was installed along the facility walls, and each witness plate is 5.08 cm in diameter, made from 0.48 cm-thick 304 stainless steel sheets of the same facility wall material. Each plate is electrically isolated from nearby grounded

structures using ceramic isolators and is 6 cm away from the facility walls. A schematic showing the location of the witness-plate array relative to the thruster exit plane is shown in Fig. 5. A 48-channel, 3-A ProXR relay switch system by Relay Pros was used to transition between witness plates. A Keithley 2470 Sourceter was used to bias each witness plate from -20 to $+50$ V in 0.1 V increments relative to the facility ground, to determine ion and electron saturation regions. A nude-type JPL design Faraday probe with a 2.31 cm diameter collector was installed 1 m away from the thruster exit plane, mounted on a rotary table. The collector was biased to -30 V with respect to ground to repel electrons and collect ions on its planar surface. The ion current density profile was collected by sweeping the probe across the entire plume and measuring the ion current density at each angular position with respect to the thruster centerline.

D. Impedance measurement diagnostic

The impedance measurement diagnostic used to measure the impedance magnitude and phase of the discharge load is shown in Fig. 6. The diagnostic consists of a frequency response analyzer, the AC power amplifier, and an isolation transformer. The Powertek GP1700 Analyzer was used as a frequency response

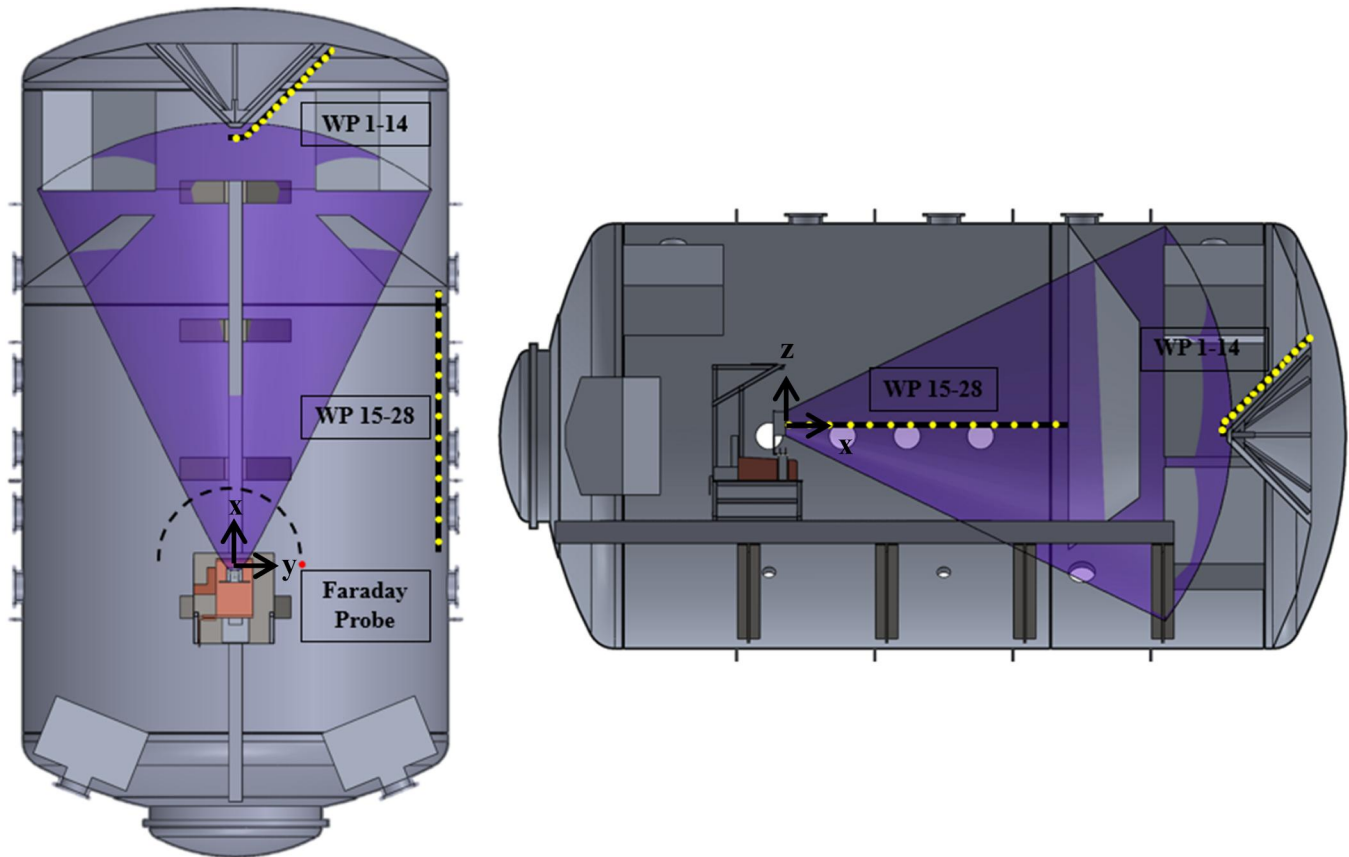


FIG. 5. Witness-plate array locations relative to the HET.

analyzer to provide the excitation signal to the discharge load, as well as record the current and voltage response due to the excitation signal. The AE Techtron 7234 power amplifier was used to amplify the excitation signal provided by the GP1700 and drive current through the coupling circuit. Additionally, the AE Techtron T2000 isolation transformer was used to couple to the discharge circuit and inject the excitation signal from the GP1700. The transformer secondary was connected in series with the cathode side of the discharge circuit. Cathode side injection was selected to keep the transformer secondary near the cathode potential relative to facility ground rather than the elevated anode potential, thereby reducing the voltage between the transformer secondary and facility ground. This arrangement was consistent with the diagnostic configuration developed by Jovel *et al.*²¹ The current response to the excitation signal was measured with a Pearson 804 current meter located less than 0.5 m from the chamber power feedthrough. Similarly, the voltage response was measured at the same location away from the chamber using a Powertek DP25 high-voltage differential probe.

Therefore, the impedance measurement reference plane was located on the air side of the chamber feedthrough, and the

uncorrected measurements included the impedance of the vacuum-side wire harness, chamber feedthrough, and electrical connections at the thrust stand. These contributions were corrected using the calibration procedure developed by Jovel *et al.*¹⁴ In this procedure, a 20- Ω resistive load, corresponding to the nominal DC load resistance at the 300 V, 15 A operating condition, was measured from 100 Hz to 300 kHz both directly at the thrust stand and outside the chamber at the impedance measurement reference plane. At each frequency, the complex difference between the measurements at the two locations was used to quantify the additional impedance of the wire harness and supporting connections. The uncorrected HET impedance was then decomposed into its real and imaginary components, and the corresponding real and imaginary components obtained from the calibration procedure were subtracted from the discharge impedance measurements. Parasitic capacitances between the electrodes and facility ground were not independently characterized.

The impedance measurements were conducted from 100 Hz to 300 kHz. This frequency range encompasses the dominant low-frequency discharge dynamics of interest, including the breathing mode, which typically occurs between approximately 10 and

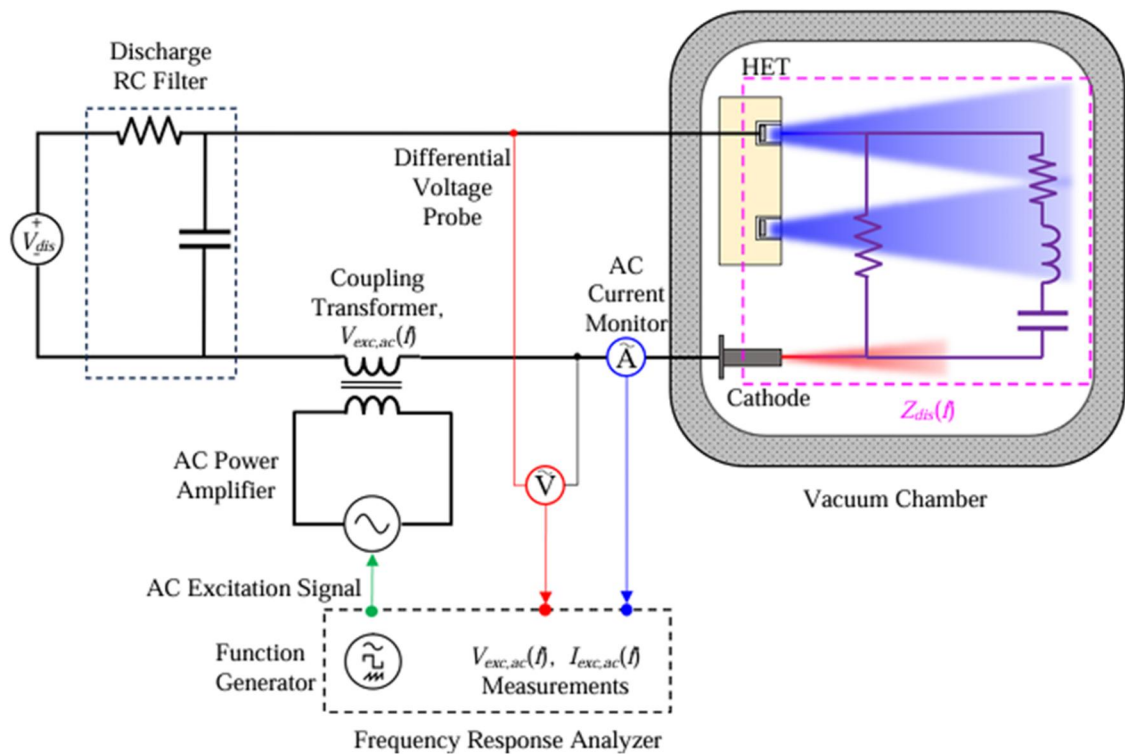


FIG. 6. Impedance measurement diagnostic schematic showing its AC coupling circuit with respect to the discharge load. Reproduced from Jovel *et al.*, J. Electr. Propuls. 3, 31 (2024). Copyright 2024 Author(s), licensed under a Creative Commons Attribution (CC BY) license.

100 kHz. Although higher frequency oscillations are known to occur, previous PSD measurements of the H9 show a substantial decrease in energy content at higher frequencies.¹⁹ In addition, the isolation transformer used in the impedance diagnostic has a specified frequency response up to 300 kHz, which limited the upper measurement frequency, whereas the AC current probe has a limited low-frequency response below 100 Hz, which constrained the lower measurement frequency.

IV. RESULTS

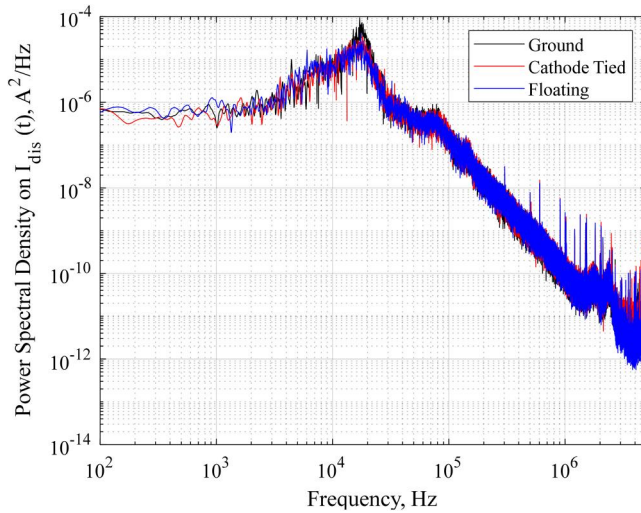
This section presents the data collected during the test campaign to examine how the thruster body electrical configurations affect current pathways and, consequently, the HET impedance profile. Time-averaged measurements for each configuration are reported, along with power spectral density profiles. Ion current

density profiles from Faraday sweeps and ion and electron saturation currents from the 28 witness plates are also shown. The impedance magnitude and phase profiles are then presented. Data were collected approximately 5 h after ignition to allow sufficient time for thruster outgassing and thermal steady-state to be reached, defined below 0.5 °C/min. The mean discharge voltage, $V_{dis,mean}$, and the mean discharge current, $I_{dis,mean}$, were held constant between configurations in order to attribute differences in datasets to the thruster body electrical configuration.

Table I shows the time-averaged characteristics of the H9 at the 300 V, 15 A thruster operating condition. The grounded configuration was the most oscillatory based on the discharge current peak-to-peak, $I_{dis,pk2pk}$, followed by the cathode-tied configuration and the floating configuration. The mean cathode-to-ground potential remained fairly constant across the three configurations. The grounded configuration exhibited a larger cathode-to-ground

TABLE I. Time-averaged characteristics at the 300 V, 15 A operating condition.

Thruster body electrical configuration	$V_{dis,mean}$ (V)	$I_{dis,mean}$ (A)	$I_{dis,pk2pk}$ (A)	$V_{CG,mean}$ (V)	$V_{CG,pk2pk}$ (V)	F_{BM} (kHz)	V_{TBG} (V)
Grounded	300.02	14.98	3.57	−17.49	15.81	15.8	0
Floating	299.98	14.99	2.98	−17.80	12.01	17.5	−4.6
Cathode tied	300.05	15.04	3.10	−18.20	12.03	18.1	−18.1

FIG. 7. PSD of I_{dis} at each thruster body electrical configuration.

peak-to-peak, $V_{CG, pk2pk}$, compared to the other two configurations. The cathode-tied configuration yielded the highest breathing mode frequency, followed by the floating configuration, and then the grounded case. It is noteworthy that the thruster body-to-ground potential is -4.6 V in the floating configuration.

Figure 7 shows the power spectral density (PSD) plots for the discharge current, I_{dis} , across all thruster body electrical configurations. The dominant oscillation in discharge current traces is typically associated with a well-known physical phenomenon in the discharge channel, the breathing mode oscillation, within the 5–80 kHz frequency range. The breathing mode oscillation arises from the difference in timescales between the ionization process and the buildup of neutral gas within the channel. The frequency with the largest amplitude in the PSD plot of I_{dis} is identified as the breathing mode oscillation and is the value reported in Table I.

The ion current density profiles at the grounded, cathode-tied, and floating electrical configurations are plotted in Fig. 8 from the Faraday probe traces. Table II provides the integrated ion beam current, I_{beam} , and divergence half-angle, θ_{div} , as recommended in Ref. 22, from each configuration, revealing nearly constant values.

The energetic beam ion population is assumed to be constant, given the high exit energy of these ions after acceleration from the discharge channel. This assumption is supported by Table II, which shows a consistent ion beam current and divergence half-angle across all configurations. The charge exchange ion population originates from inelastic collisions between high-energy ions and slow-moving neutral atoms, resulting in a population of slow-moving ions. At the measured facility pressures, assuming a neutral-gas temperature of 300 K and a CEX cross section of $4.4 \times 10^{-19} \text{ m}^2$ for representative 300-eV krypton ions,²³ the estimated CEX mean free path was 13.1–13.6 m. Although this value exceeds the facility dimensions, CEX production remains relevant

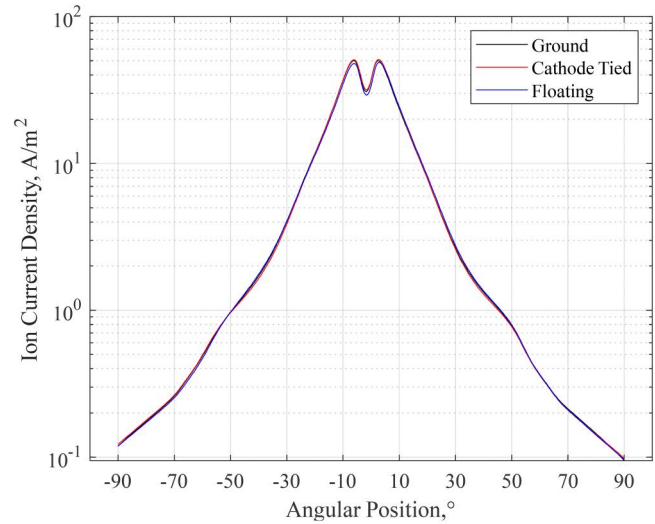


FIG. 8. Ion current density as a function of angular position.

over the meter scale beam trajectories within the chamber, as demonstrated by previous current pathway measurements in the same facility.²⁴ The neutral population is assumed to remain constant across all three configurations, as the background pressure varied by less than 3.8% between cases. Given the constant neutral density and beam divergence, the CEX ion population may also be assumed to remain mostly unchanged.

Witness plates 1–14 are located in the plume region, as determined by the divergence half-angle provided in Fig. 5, while witness plates 15–28 are positioned outside the plume, in the background plasma region. The ion and electron saturation currents from witness plates 1–14 are shown in Fig. 9. The ion saturation current for the grounded configuration ranged from 2.4×10^{-4} to 6.9×10^{-3} A and from 2.6×10^{-3} to 1.7×10^{-2} A for the electron saturation current. The ion saturation current for the floating configuration ranged from 2.1×10^{-4} to 3.3×10^{-3} A and from 2.6×10^{-3} to 1.3×10^{-2} A for the electron saturation current. The ion saturation current for the cathode-tied configuration ranged from 2.3×10^{-4} to 7.6×10^{-3} A and from 2.9×10^{-3} to 1.8×10^{-2} A for the electron saturation current. Figure 9 shows that the cathode-tied electrical configuration results in higher electron saturation current in witness plates 1–14. Aside from witness plate 1, there are no discernible differences in the ion saturation current values among the remaining witness plates.

TABLE II. Plume characteristics at the 300 V, 15 A operating condition.

Thruster body electrical configuration	I_{beam} (A)	θ_{div} (deg)
Grounded	12.2	17.7
Floating	12.2	18.1
Cathode tied	12.3	18.0

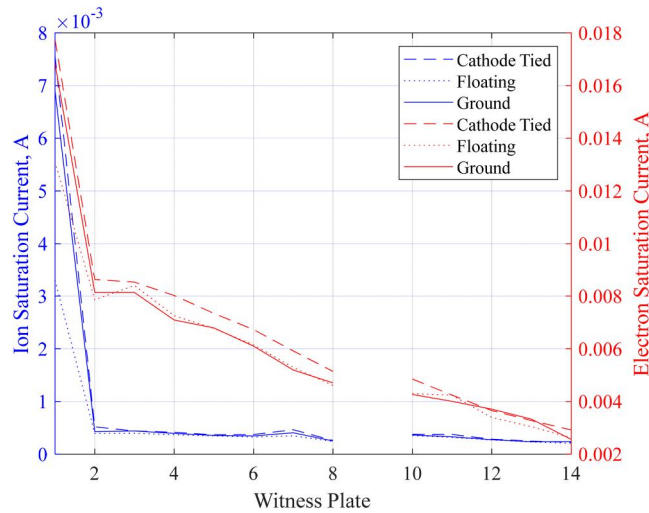


FIG. 9. Ion and electron saturation current measurements from witness plates 1–14. Witness plate 9 omitted due to the loss of electrical isolation to ground.

Similarly, the ion and electron saturation currents from witness plates 15–28 are shown in Fig. 10. In the grounded configuration, ion saturation current ranged from 1.3×10^{-5} to 2.7×10^{-4} A and the electron saturation current from 4.1×10^{-4} to 4.7×10^{-3} A. In the floating configuration, ion saturation current ranged from 1.2×10^{-5} to 2.1×10^{-4} A and the electron saturation current from 3.4×10^{-4} to 4.5×10^{-3} A. In the cathode-tied configuration, ion saturation current ranged from 1.2×10^{-5} to 3.2×10^{-4} A and the electron saturation current from 4.2×10^{-4} to

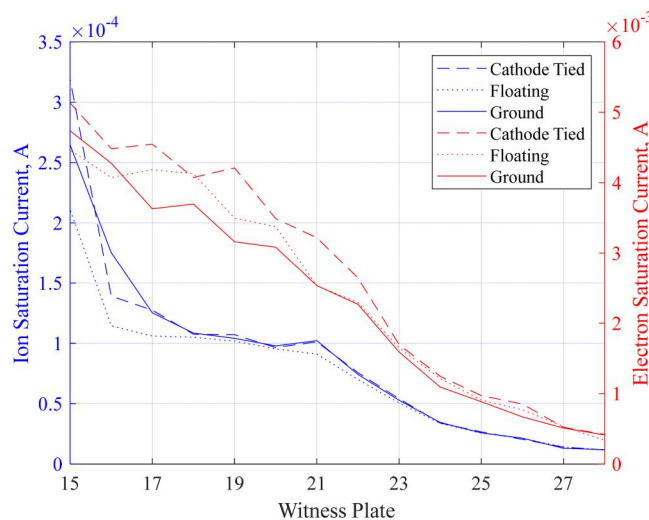


FIG. 10. Ion and electron saturation current measurements from witness plates 15–28.

5.1×10^{-3} A. Consistent with trends observed in plume region witness plates, background plasma witness plates also indicate an increase in electron saturation current in the cathode-tied configuration. Additionally, witness plates 16–21 reveal a regional trend in which the floating configuration produces the second-highest electron saturation current, followed by the grounded configuration. Also, while the Faraday traces indicate an approximately constant charge exchange ion population, Fig. 9 suggests some variation in the CEX ion population near the facility walls. Since witness plates 15–28 are located outside the core plume region, where CEX ions are the dominant ion species, differences in the ion current flux measured at these locations may indicate that the CEX population is influenced by the thruster body's electrical configuration.

The impedance magnitude and phase of the discharge load from 100 Hz to 300 kHz for each thruster body configuration are presented in Figs. 11 and 12, respectively. From 100 Hz to 2 kHz, the grounded configuration exhibits the highest impedance magnitude, reaching 1.78Ω . Within this frequency range, there is no distinct difference between the cathode-tied and floating configurations, both averaging an impedance magnitude of approximately 1.7Ω . Between 2 and 20 kHz, the impedance magnitude for all configurations rises rapidly and forms a distinct peak. Figure 12 shows that the phase reaches a trough near the frequency at which the impedance magnitude profile peaks. The first peak in the impedance magnitude profile occurs at 15.47 kHz for the grounded configuration with a value of 6.71Ω . The dominant peak for the cathode-tied configuration appears at 15.89 kHz with a magnitude of 5.24Ω . For the floating configuration, the peak occurs at 14.89 kHz with a magnitude of 5.01Ω . Additionally, the ground configuration is the only case in which the phase transitions from a positive to a negative value at the peak frequency, consistent with resonant behavior. Another clear peak around 130 kHz is present in all configurations in both Figs. 11 and 12.

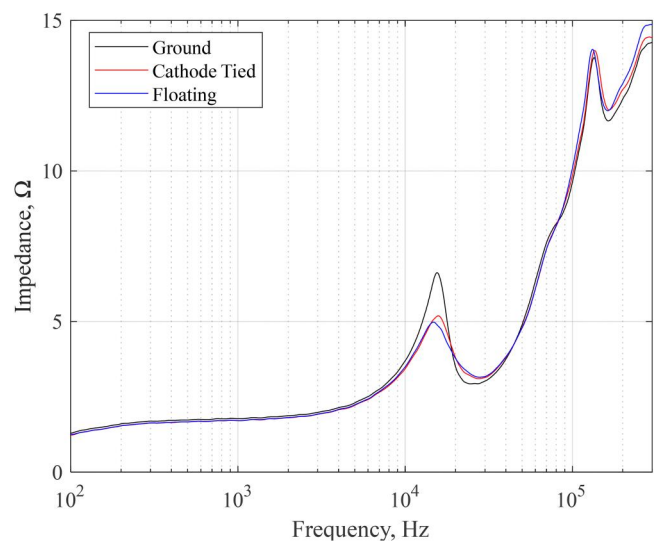


FIG. 11. Impedance magnitude of the HET discharge.

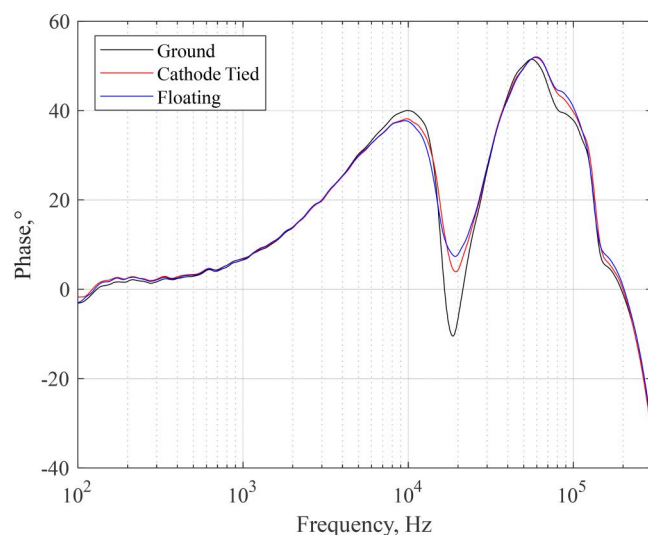


FIG. 12. Impedance phase of the HET discharge.

The second peak in the impedance magnitude occurs at 134.15 kHz for the ground configuration with a value of $13.9\ \Omega$. The next peak in the cathode-tied configuration appears at 135.89 kHz with a magnitude of $14.1\ \Omega$. For the floating configuration, the peak occurs at 132.43 kHz with a magnitude of $14.1\ \Omega$.

V. DISCUSSION

In this section, the impact of the thruster body's electrical configuration on (1) thruster operating conditions, (2) far-field electron current pathways, and (3) discharge impedance is discussed, building on the data reported in Sec. IV. The current pathways model for each configuration will be referenced to support the conclusions drawn across the datasets.

A. Impact of thruster body electrical configuration on far-field current pathways

Table I indicates that the breathing-mode frequency is highest in the cathode-tied configuration, followed by the floating and grounded configurations. Although the breathing-mode frequency depends on the ionization and acceleration dynamics within the discharge channel, the present measurements do not directly resolve the ion velocity or the spatial extent of these regions.¹¹ Therefore, the observed frequency differences cannot be attributed uniquely to changes in the ionization or acceleration-zone length. In an LIF study of the HERMeS Hall thruster, Huang *et al.* found that the axial acceleration profile was largely unchanged between cathode-tied and grounded body operation and shifted only slightly upstream when the body was floating.¹² Although HERMeS is a larger thruster and was tested in a different facility, those measurements demonstrate that configuration-dependent changes in discharge behavior do not necessarily correspond to large changes in the acceleration zone structure. The frequency differences measured in the present study therefore indicate that

the thruster body electrical boundary condition modifies the discharge dynamics. Direct internal plasma measurements would be required to determine whether changes in the ionization or acceleration regions also contributed.

The thruster operating parameters presented in Sec. IV agree well with the results reported by Peterson *et al.*¹¹ Their measurements also show that the grounded configuration yields the lowest breathing mode frequency and the largest discharge current peak-to-peak values among the configurations. However, their results indicate that the thruster body potential with respect to ground in the floating configuration is lower than in the cathode-tied configuration. This difference between the data sets may be due to differences in the experimental setup. Specifically, NASA electrically isolates nearby ground surfaces out to 1 m using a Kapton tape. As stated in Sec. III A, nearby conductive surfaces to the thruster, such as the thrust stand pedestal, remained electrically tied to facility ground, which may explain why the floating thruster body potential is smaller in the present study than in Ref. 11. These differences may have contributed to the measured floating body potential and breathing mode frequency trend, although this facility effect was not isolated in the present measurements. This observation further supports the importance of understanding the impact that near-field conductive surfaces have on the overall discharge.

Moreover, Figs. 9 and 10 reveal a distinct trend in the electron population near the facility walls. The cathode-tied configuration yielded the highest electron saturation current values for nearly all witness plates. The cathode-tied configuration imposes the most negative electrical boundary condition at the thruster body relative to ground. As a result, it is the most electron-repelling configuration, which would lead to an increased flux of electrons toward the grounded facility walls. This explains the elevated electron population near the walls observed under the cathode-tied configuration. Additionally, Fig. 10 shows that the grounded configuration resulted in the lowest electron saturation current near the facility walls in almost all the background plasma witness plates. In contrast to the cathode-tied case, the grounded thruster body presents the most positive electrical boundary condition with respect to ground. Consequently, it is the most electron-attracting configuration, which would lead to a decreased flux of electrons toward the grounded facility walls, as the electrons have a less resistive path to ground through the thruster body itself. Therefore, the thruster body surface shortens the ion-electron recombination through the facility walls in a grounded configuration. The results indicate that electron current pathways are impacted by thruster body electrical configuration and help explain the trends observed in the thruster operating parameters. Because electron current pathways define how the discharge electrically couples to the thruster body and facility ground, changes in these pathways are expected to modify the effective discharge impedance. The H9 employs conductive front pole covers electrically connected to the thruster body. Therefore, the present results are most directly applicable to HET configurations with conductive plasma-facing pole covers at the thruster-body potential. HETs employing dielectric pole covers may exhibit different plasma-surface current pathways, and the quantitative influence of thruster-body electrical configuration may therefore differ.

B. Impact of thruster body electrical configuration on HET discharge impedance

The impedance magnitude and phase profiles also show a clear trend across the thruster body electrical configurations. The grounded configuration exhibits a consistently higher impedance magnitude between 100 Hz and 18.3 kHz than the other configurations. Since the breathing mode frequency ranges from 15.8 to 18.1 kHz, the impedance magnitude profile indicates that the grounded configuration maintains the highest impedance up to approximately the breathing mode frequency. Because the breathing mode oscillation is the dominant and most energetic mode, as shown in the power spectral density plot in Fig. 7, the grounded configuration maintains the highest impedance across the frequency band containing the greatest spectral energy in the discharge-current signal.

Within this frequency band, the first impedance magnitude peak in the grounded configuration occurs at 15.47 kHz and is accompanied by a positive to negative phase transition. This frequency is close to the independently measured breathing-mode frequency of 15.8 kHz for the grounded configuration. Jovel *et al.* identified similar resonant behavior near the breathing mode based on the impedance magnitude and phase characteristics of a HET discharge. The correspondence observed here suggests that the feature is associated with the breathing-mode plasma dynamics. However, the phase transition occurs only in the grounded configuration, indicating that the resonant characteristics are also sensitive to the thruster body electrical boundary condition. The present measurements do not establish whether the feature originates entirely within the plasma or includes a contribution from the configuration-specific electrical connections. It is therefore described as configuration-dependent resonant behavior near the breathing mode rather than being assigned exclusively to either a plasma-related or circuit resonance.

The impedance profiles were corrected for the additional impedance introduced by the vacuum side wire harness, chamber feedthrough, and supporting discharge-circuit connections using the calibration procedure developed by Jovel *et al.*¹⁴ as described in Sec. III. The remaining anode and cathode discharge harness, power supply, and discharge filter were unchanged among the three configurations, and the same calibration correction was applied to each measurement. Although the frequency-dependent output characteristics of these components remained part of the implemented discharge system, they were not independently varied among the configurations. No direct impedance signatures were observed at the power supply switching frequencies of 600 Hz and 57.6 kHz or in an identifiable sequence of their harmonics.

In contrast, the configuration specific thruster-body connections were not included in the main discharge-harness calibration. Other parasitic contributions, including capacitances between the electrodes or thruster body to facility ground, were not characterized separately. For the cathode-tied configuration, these uncharacterized contributions include the impedance of the approximately 118-ft, unpaired thruster-body lead. This lead is in series with the thruster body-to-cathode current pathway rather than with the entire discharge load. Because the current through

this pathway was not measured independently, the contribution of the lead could not be separated from the measured impedance response. The reported profiles therefore represent the effective discharge load impedance of each implemented thruster-body electrical configuration. The configuration-dependent differences in the impedance profiles coincide with differences in the witness-plate electron saturation currents. The cathode-tied configuration produces the highest electron saturation current at nearly all witness plates, whereas the grounded configuration produces the lowest values at nearly all background plasma locations. These independent measurements support the interpretation that the thruster body electrical configuration redistributes far-field electron current pathways.

Figure 13 presents the resistance and reactance calculated from the impedance magnitude and phase profiles. The sign and magnitude of the reactance indicate that both inductive and capacitive behavior occur over the investigated frequency range. The grounded configuration exhibits the most pronounced reactance transition near the breathing mode frequency and is the only configuration that transitions from positive to negative reactance near the first impedance peak. The grounded configuration also exhibits the largest naturally occurring discharge current peak-to-peak oscillations. The plasma-sheath capacitance represented in the current pathways model provides one possible contribution to the measured reactive response. However, an equivalent sheath capacitance cannot be extracted independently of the inductive and configuration specific connection contributions from the present measurements. The coincident reactance and discharge current trends are therefore consistent with, but do not uniquely identify, a contribution from plasma-sheath capacitance.

Taken together, the measurements demonstrate that changing the implemented thruster body electrical configuration changes both the effective discharge impedance and the far-field

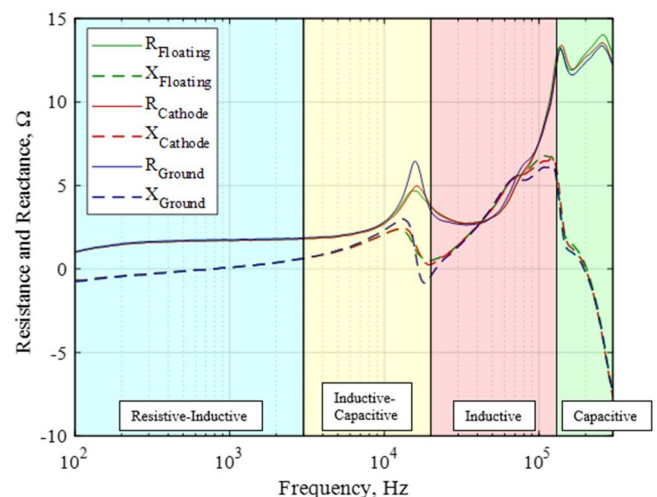


FIG. 13. Resistance, R , and reactance, X , profiles at the 300 V, 15 A condition.

electron-collection distribution. The correspondence between the first impedance peak and the independently measured breathing mode frequency supports the association of this feature with the breathing mode plasma dynamics. However, the present measurements do not quantify the relative contributions of changes in the plasma response and configuration-specific connection impedances to the differences in impedance magnitude and phase among the configurations.

VI. CONCLUSION

The thruster-body electrical configuration produced measurable changes in both the effective discharge load impedance and the far-field electron collection distribution. The grounded configuration exhibited the highest impedance magnitude over the frequency range containing the dominant breathing mode oscillation, the largest discharge current peak-to-peak oscillations, and a positive to negative phase transition near the first impedance peak. Independently, the witness-plate measurements showed that the cathode-tied configuration produced the highest electron saturation currents at nearly all measurement locations, whereas the grounded configuration produced the lowest values at nearly all background plasma locations. These results demonstrate that changing the thruster body electrical configuration alters both the discharge response and the distribution of far-field electron current pathways.

The reactive response of the grounded configuration is consistent with a possible contribution from plasma-sheath capacitance. However, the present measurements do not isolate this contribution from other reactive effects, including those associated with the configuration-specific electrical connections. The results therefore establish the conductive thruster body as an electrical boundary condition that should be considered when interpreting Hall-thruster dynamics, discharge impedance, and electrical facility effects. The quantitative trends reported here are most directly applicable to thrusters employing conductive plasma-facing pole covers electrically connected to the thruster body.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Janice D. Cabrera: Conceptualization (equal); Data curation (equal); Formal analysis (equal); Investigation (equal); Methodology (equal); Writing – original draft (equal); Writing – review & editing (equal). **David R. Jovel:** Conceptualization (equal); Formal analysis (equal); Writing – review & editing (equal). **Mitchell L. R. Walker:** Conceptualization (equal); Formal analysis (equal); Writing – review & editing (equal).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

NOMENCLATURE

F_{BM}	=	Breathing mode frequency, Hz
I_{beam}	=	Beam ion current, A
I_{dis}	=	Discharge current, A
I_{sp}	=	Specific impulse, s
V_{CG}	=	Cathode-to-ground potential, V
V_{dis}	=	Discharge voltage, V
V_{TBG}	=	Thruster body-to-ground potential, V

Greek

θ_{div}	=	Divergence half-angle, deg
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