Alteration of Ion Plume by Central Segmented Electrode in a Wall-less Hall Thruster

IEPC-2022-395

Presented at the 37th International Electric Propulsion Conference
Massachusetts Institute of Technology, Cambridge, MA USA
June 19-23, 2022

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Abstract: Wall-less Hall thrusters utilize the entire thruster area to accelerate ions, however the interaction between the plasma in the center of the thruster and that near the anode is understudied. Measurements have shown the central plasma is accelerated further downstream than the plasma near the anode, resulting in cone-like potential structures and large plume divergence, which lowers efficiency. A method to control the central plasma structure was investigated by the inclusion of a positively biased central electrode. Measurements of the ion energy and plume suggest biasing this electrode positively pushes the central acceleration region further downstream, separating the ionization and acceleration region, which improved deposition of energy into ions. However, given that the central acceleration region is further downstream, this came at the cost of higher plume divergence.

Nomenclature

I_i	=	ion current
IEDF	=	ion energy distribution function
R	=	plume probe-thruster distance
RPA	=	retarding potential analyzer
sccm	=	standard cubic centimeters per minute
θ	=	probe angle
θ_{half}	=	momentum-weighted half-plume angle

I. Introduction

Wall-less Hall thrusters are a promising thruster configuration to enable high-lifetime due to the absence of channel walls and minimal plasma-facing material to erode. These thrusters have shown relatively low efficiency compared to conventional annular Hall thrusters, in large part due to the high plume divergence as ions are accelerated at large angles [1]–[6]. This plume divergence is caused by radial electric fields which form in the thruster in part due to the large diverging axial magnetic fields in the thruster center (Figure 1). Furthermore, recent measurements of the plasma potential

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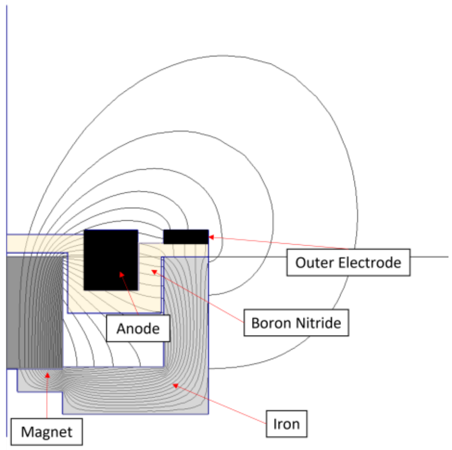

Figure 1. Magnetic Field Lines and schematic of the MET wall-less Hall Thruster

in the center of the thruster have shown potentials as high as the applied anode voltage, with electric field profiles and thrust density magnitudes similar to that in the acceleration region near the anode [6]. However, this central acceleration region appears to form downstream that of the anode acceleration region. The resulting outward-pointing radial electric fields that form between the center and the anode of the thruster appears to greatly contribute to the plume divergence, as shown in the sketch of Figure 2.

Given that the central electric fields are generated along the magnetic field lines and are larger than the plasma pressure gradient, the mechanism of formation of this central electric field is unclear [6]. However by utilizing electron temperature anisotropy levels found in particle in cell simulations, the electric field due to magnetic

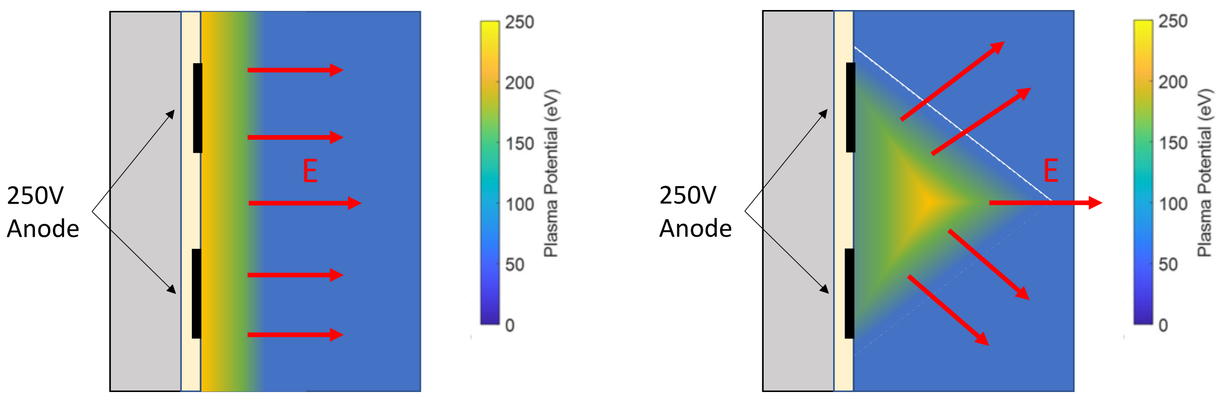

Figure 2. (Left) sketch of a flat potential profile with axial electric fields. (Right) sketch of a uneven potential profile with downstream acceleration region in the center, causing radial electric fields.

mirroring was calculated to be comparable to this component [6]. Thus, it was hypothesized that by modifying the electron temperatures in this region, the location of this drop in plasma potential could be altered. Similar to previous works utilizing segmented electrodes in Hall thrusters to control potential profiles [7], [8], a wall-less Hall thruster with a central electrode and gas distributor in addition to the conventional anode was developed, as shown in Figure 3. This design is expected to provide some ability to control this central potential structure, with the goal of moving the central acceleration region upstream and to reduce plume divergence. This electrode was biased positively due to the highly positive plasma potentials measured in the axially diverging central magnetic field, which is a different approach than that taken by thrusters with centrally mounted cathodes. Hall thrusters with similarly large diverging axial fields have been operated with central cathodes, however it has been reported that this configuration appears to lower thrust and decrease the operating envelope [9].

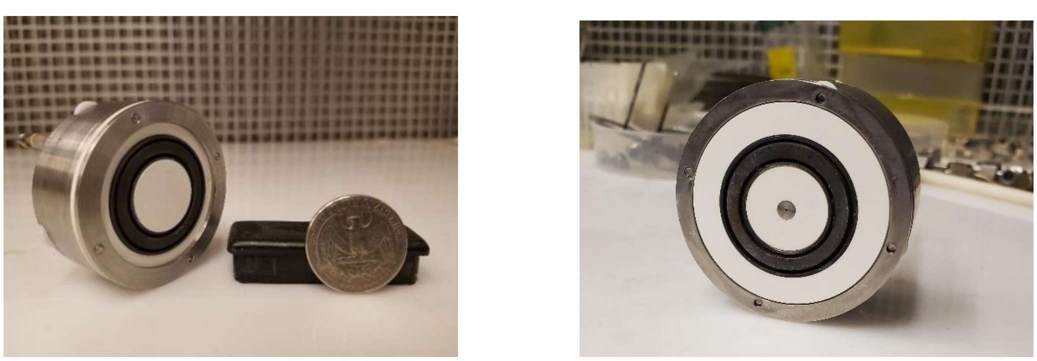

Figure 3. Two variants of wall-less Hall thruster: (left) thruster with Boron Nitride in the center and (right) thruster with a steel gas distributor electrode in the center.

II. Experimental Setup

The described experiments were performed at the Princeton Plasma Physics Laboratory in the large vacuum facility of the Hall Thruster Experiment (HTX). This facility consists of a 28 m^3 vacuum vessel equipped with a variety of plasma diagnostics. This HTX facility is described elsewhere [10]. The thruster was operated with xenon, the flow of which was measured by a MKS flow controller with full scale of 15 sccm and ±0.1 sccm uncertainty. A commercial hollow cathode was used as a cathode neutralizer, and was operated with a xenon flow rate of 2 sccm and cathode keeper current and voltage of 1.3 A and 20V. During the following experiments, the background gas pressure in the chamber did not exceed 2 μTorr.

The plume was investigated with an ion flux probe and retarding potential analyzer (RPA) located on a rotating positioner [11], [12]. The distance between the probes and the thruster frontal surface is 73 cm. The ion flux probe was biased to -40V to operate in the ion current saturation regime. Total ion current (I_i) was determined by integrating the measured ion current density j_i over the probe angle (θ) with a fixed probe distance (R) and assuming azimuthal symmetry:

$$I_i = \pi R^2 \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} j_i \sin\theta \, d\theta \, . \tag{1}$$

The momentum-weighted half-plume angle (θ_{half}), a measure of the divergence of the plume, was determined from these same measurements by taking the arc cosine of the ratio of the total axial ion current to the total ion current:

$$\theta_{half} = cos^{-1}\left(\frac{\pi R^2 \int_{-\pi/2}^{\pi/2} j_i \sin\theta \cos\theta \, d\theta}{I_i}\right). \tag{2}$$

The retarding potential analyzer used in this experiment was a two-grid system [13]. This system measures ion energy distribution functions (IEDF) by biasing a sweeping positive voltage to the first grid, which screens out ions with energy lower than the applied voltage. The second grid is biased negatively to repel electrons, and current is collected by a negatively biased ion flux probe situated behind these grids. The IEDF is found by taking the derivative of the collected current with respect to the sweeping voltage. Both plume diagnostics have been used extensively in previous works [11], [12], [14], [15, p.].

III. Ion Energy Distribution

Ion energy distributions were measured at four angles with respect to the thruster axis: 0, 30, 60, and 90 degrees. These measurements were conducted when the anode voltage was biased to 250V with 4 sccm Xenon through the anode gas distributor, and the voltage on the central electrode was varied from floating (~+20V) up to 200V. Note that the central electrode voltage did not exceed 200V during experiments, as when the central electrode bias approaches that of the anode bias, the current through the central electrode increases rapidly and the central electrode becomes very hot. The resulting IEDFs are shown in Figure 4, where the data suggests that higher voltages on the central electrode both increases the energy of the accelerated ions and decreases the spread of energy such that the distribution is narrower. Interestingly, a high voltage central electrode also maintains high ion energies even at 90 degrees off-axis, whereas without this bias the ion energies are so low as to be unable to be resolved. This reduction in off-axis ion energy is typical in Hall thrusters, as the ions which reach a probe 90 degrees off-axis are typically not accelerated by the full voltage drop [16]. For there to not only be a clear and resolvable ion energy distribution, but for it also to be close to the anode potential, suggests that ions undergo significant radial acceleration by radial electric fields. Note that in the previous design of this wall-less Hall thruster without the central electrode, high ion energies were also measured at large angles, while this appears to not be the case in this iteration unless the central electrode is positively biased [6].

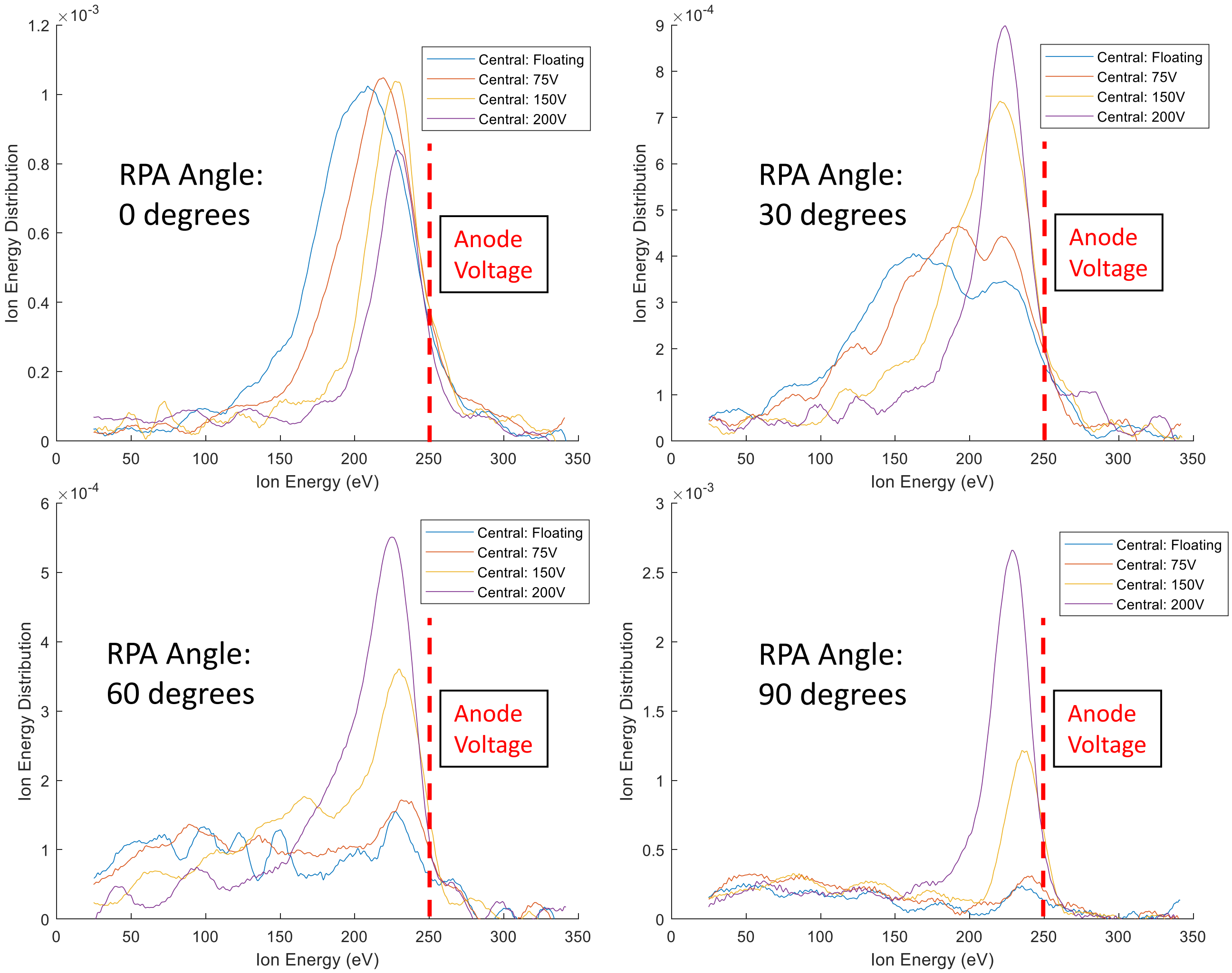

Figure 4. Ion Energy Distribution Function measurements over multiple probe angles for wall-less Hall thruster with 250V anode and various voltages of central electrode bias

Typically, in Hall thrusters the ionization region and acceleration region overlap somewhat, which causes the spread in ion energies as some ions are born at lower potentials. The increase in ion energy and reduction in the full-width half-maximum of the ion energy distributions suggests that as the central electrode voltage increases, the overlap between the ionization region and the acceleration region is decreasing. This suggests some movement of either the ionization upstream or the acceleration region downstream.

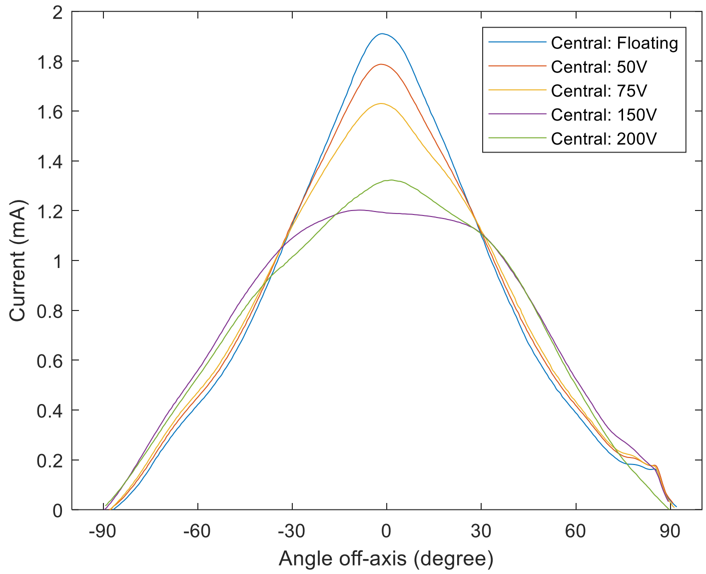

Figure 5. Plume distributions of a wall-less Hall thruster 4sccm Xenon flow, 250V applied to the anode, and varying central electrode voltages

IV. Plume Angle

Plume distributions were similarly measured at a variety of central electrode biases and for a wall-less Hall thruster with 250V applied to the anode and 4 sccm Xenon through the anode gas distributor. The resulting plume distributions (Figure 5) indicated that as the central electrode increases in voltage, the plume became more diffuse. At low central electrode voltages, the on-axis ion current density was up to 60% higher than that measured at high central voltages. Despite the lower on-axis current, the total current and propellant utilization did not appear to change significantly – the propellant utilization stayed within 2% of the initial value which was within the range of uncertainty for these measurements. This is due to a larger ion current observed at the higher angles of the plume distribution.

The momentum-weighted half-plume angle θ_{half} as calculated by Eq. (2) was observed to increase with the central bias from 39 degrees to about 43 degrees (Figure 7). This, in conjunction with the apparent separation of the ionization and acceleration region, implies that it is the acceleration region that is moving downstream in the center of the thruster. Given that the ions which appear at high angles have energies as high as 250V when the central electrode is 200V, it appears that a plasma potential higher than that applied to the central electrode appears in the center of the thruster. That is, to measure ions with 250eV of kinetic energy at angles 90 degrees from the thruster axis, the ions must be accelerating along a field-line that is predominantly radial. This implies the plasma potential in the thruster center is at least as high as the anode-region plasma potential, if not higher. Given that the central electrode was always biased below the anode, this suggests the plasma potential in the center rises from the central electrode potential, and there must correspondingly be an electric field pointing from the central plasma towards the center electrode – in the opposite direction than the remainder of the plasma.

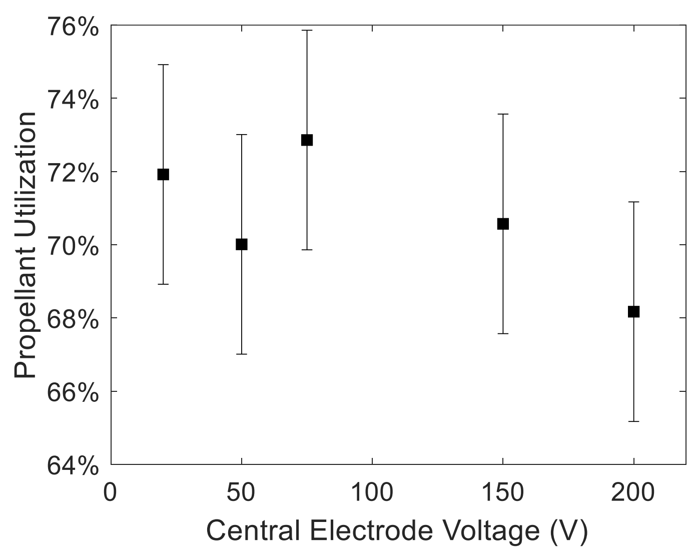

Figure 6. Propellant utilization remaining relatively constant as central electrode bias increases for a wall-less Hall thruster 4sccm Xenon flow and 250V applied to the anode.

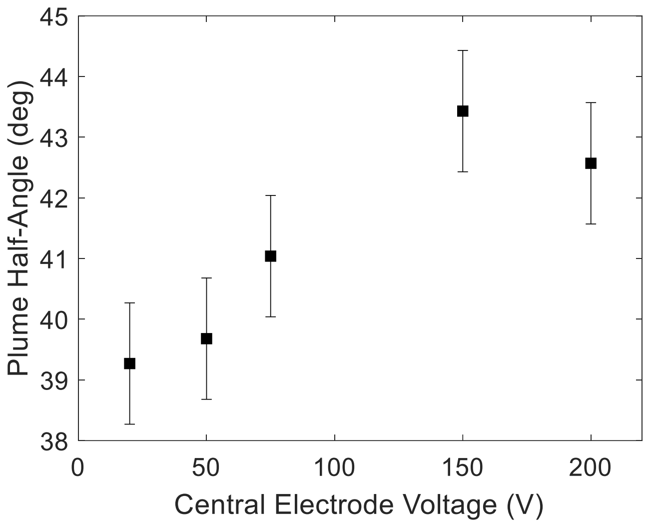

Figure 7. Half-plume angle increases with central electrode bias for a wall-less Hall thruster 4sccm Xenon flow and 250V applied to the anode.

The mechanism for the formation of these larger plasma potentials have been discussed in previous works [6], and may be due to the magnetic mirror generating axial electric fields or some instability increasing electron mobility between the anode and central region. Both the magnetic mirror and instability hypothesis are driven by the strong axial magnetic field gradients. For the former, the large gradients inhibit electron axial flow due to magnetic mirroring, resulting in large electric fields to develop to balance the forces and allow steady-state flow. For the latter, the restricted electron mobility axially is compensated by enhanced mobility between high-potential regions such as near the anode, which essentially "shorts" the anode and central regions together and increases the central potential. Further measurements of the plasma properties would provide insight into the mechanisms at play, which is critical towards understanding how to control this central region.

Figure 8. Wall-less Hall Thruster operating with positively biased central electrode

V.Conclusions

The ability to control the plasma potential in the center of a wall-less Hall thruster may be critical to enabling the wall-less configuration as a viable thruster for spacecraft use. Experiments have demonstrated that biasing the central electrode provides some ability to control the plasma potential structure in this region. Further work is needed to verify the hypotheses behind the mechanisms of these changes, which could be achieved by dedicated plasma potential studies or Laser Induced Fluorescence measurements of the ions. The movement of the acceleration region downstream of the center was the complete opposite of the desired effect of biasing the central electrode, however it does demonstrate the ability to separate the ionization and acceleration region. Given that thrust increases and plume focusing was observed when biasing the outer electrode [8], some combination of biasing the inner and outer electrode may lead to favorable performance outcomes. Future work should be involved in mapping the complete radial and axial measurements of the plasma potential while biasing these electrodes. Other methods to alter the central potential structure, such as by flowing gas through the center, may also be fruitful. Measurements of the central plasma potential as the central electrode voltage and gas flow is changed will be critical to our understanding of how these thrusters function.

Acknowledgments

This work is partially supported by the AFOSR and the United States Department of Energy. The authors wish to thank Professor Andrei Smolyakov for fruitful discussions.

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