

EEDF Control of a Hall Thruster Plasma Using a Downstream Reverse Orientation Cathode

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The goal of this study was to develop an easily implementable method to tailor the energies of the electrons to increase total thruster efficiency, specifically through improving ionization. The proposed method investigated in this study was to place the cathode downstream and reverse its orientation so that it was facing the thruster channel. The intent behind this placement was to decrease the electron's path to the channel in the hopes that this energy would instead be used in ionizing more neutrals. Using the H6, performance measurements were taken at 300 V and 150 V with a 20 mg/s anode flow rate, and with the thruster body floating to more closely mirror operating conditions in space. Thrust, thrust-to-total power, total thruster efficiency, and charge utilization efficiency are presented in this paper. For the 300 V condition, the total thruster efficiency increased by a few percentage points with the external, downstream cathode. Charge utilization efficiency remained about the same within the error propagated uncertainty for running the thruster with the centrally mounted cathode compared to operation with the downstream cathode for both the 150 V and the 300 V conditions. Additionally, a new method for analyzing ExB probe data was introduced that allows straightforward analysis of probe traces, even where distinct peaks are not immediately visible throughout, and that regiments the process in a way that eliminates additional biases from being introduced through the analysis procedure. This new method also revealed that the part of the trace representing the singly charged xenon ion population is actually made up of two distinct distributions possibly corresponding to two separate ionization zones within the thruster, which is consistent with Haas' results where he took axial, internal Hall thruster channel measurements using Langmuir probes.

Nomenclature

D_T	= thruster diameter
I	= current
I_D	= thruster's discharge current
I_i	= total current collected by the ExB probe for the i^{th} ion species
$\dot{m}_A$	= propellant mass flow rate through the anode
$\dot{m}_C$	= propellant mass flow rate through the cathode
$\dot{m}_T$	= total mass flow rate ($\dot{m}_A + \dot{m}_C$)
P_D	= thruster's discharge power
P_{tot}	= total thruster power, discharge power plus magnet power

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R	= radius from thruster centerline
R^2	= the R-squared value, a statistical assessment of how close the data are to the fit function
$R_{channel}$	= thruster channel radius measured from thruster centerline
SD	= the average standard deviation of each point from the fit function
T	= thrust
V	= voltage
V_{c-g}	= cathode-to-ground voltage
V_D	= thruster's discharge voltage
$V_{f,thruster}$	= thruster body floating voltage
V_{keeper}	= cathode's keeper floating voltage
V_{mp}	= most probable voltage
V_o	= offset voltage
Z	= linear distance downstream normal to thruster exit plane
Z_i	= charge of the i^{th} ion species
η_q	= charge utilization efficiency
η_{tot}	= total thruster efficiency
σ	= standard deviation
χ^2	= the reduced chi-squared value, chi-square/degrees of freedom (dof), a statistical measure of the goodness-of-fit
Ω_i	= current fraction of the i^{th} ion species

I. Introduction

CONTROLLING the Electron Energy Distribution Function (EEDF) in Low Temperature Plasmas (LTPs) has been the subject of many experimental, theoretical and computer generated investigations. There is great interest in this pursuit because electron processes directly influence certain reaction rates in the discharge, plasma parameters and the efficiency of the process or device that utilizes these plasmas.¹⁻⁸ For instance, as the driving mechanism in Hall Effect Thrusters (HETs), the partially ionized LTP and the complexities of its interaction with the electromagnetic inputs of the device are still being studied aggressively in the hopes of understanding the processes that cause some of the behaviors that are being observed. In particular, one of the unanticipated behaviors is the anomalously high transport of electrons across the magnetic field and the impact of this lack of full control on the confinement of these electrons on ionization and thruster efficiency.⁹⁻¹⁵ This makes the pursuit of EEDF tailoring in HETs an interesting and challenging task, and perhaps looking for ways to change the EEDF to increase efficiency (and therefore increase confinement) is another path towards understanding the anomalous electron cross-field transport. Hence the question was posed as to whether there is a way to tailor the energies of the electrons to increase HET efficiency, specifically by improving ionization.

The ionization cost per beam ion is currently 122 eV/ion for the H6, a state-of-the-art 6-kW thruster, at its nominal operating condition of 300 V 20 A, even though the first, second and third ionization energies of xenon are around 12 eV, 21 eV and 32 eV respectively. Another parameter of interest is the ionization fraction, which is 10%. This parameter is usually compared to the mass utilization efficiency. However, the mass utilization is a measure of the flux of ions to the total incoming flux of neutrals from the anode, so it is a number density times a velocity, while the ionization fraction compares the number density of ions to the number density of neutrals. The ionization fraction in Hall thrusters is around 10%. However, the velocity of neutrals in a thruster is around 100 m/s, while that of the ions is around 10 km/s— 2 orders of magnitude higher.¹⁶ So, even though the density of ions is a tenth of that of the total flow, because their velocity is so much higher, the mass utilization efficiency is very high.

The aim of this study was to find a way to manipulate electron energies to accomplish an increase in thrust and efficiency by increasing the ionization fraction resulting in a decrease in the cost per beam ion. To achieve this in a way that would not require additional power sources or additional thruster components, the hollow cathode, which is the thruster's source of ionizing and neutralizing electrons, was placed downstream of the thruster. The cathode was oriented so that it was outside the densest part of the plume, and so that the cathode's orifice was pointing towards the thruster. The intention behind this placement was to allow a more direct path for the electrons to the channel exit plane where the Hall current, responsible for ionizing gas propellant, is formed.

This paper will focus on the results from the thrust stand, from which thrust, thrust-to-total power, and total thruster efficiency were calculated, and the ExB probe, which measures ion species fractions and charge utilization efficiency. These values, for the downstream, reverse orientation cathode, will be compared to the corresponding values with standard H6 operation with a centrally mounted cathode to determine how this EEDF control method affects these aspects of thruster function and to determine what this can tell us about the intricacies of the interaction between the electrons and the crossed electric and magnetic fields of this LTP device.

II. Experimental Equipment, Setup and Methods

A. Vacuum Facility

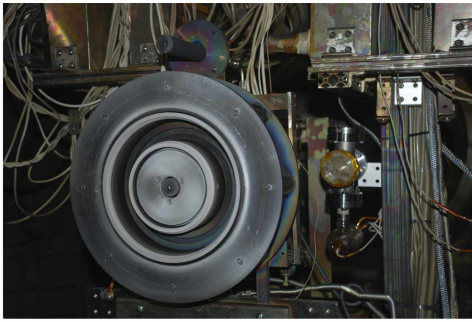
These experiments were carried out at the Large Vacuum Test Facility (LVTF) at PEPL. This vacuum chamber, measuring 9 m long and 6 m in diameter is roughed down to 100 mTorr by two roots-type blowers each with a pumping speed of 2,000 ft³/min and four rotary gas ballast mechanical pumps each capable of 400 ft³/min. The chamber is then brought to high vacuum using seven PHPK TM-1200s with a total pumping speed of 500,000 liters per second (l/s) on air and 240,000 l/s on xenon. In these experiments, which used flow rates of 20 mg/s in all the operating conditions tested, with a 7% cathode flow fraction (CFF), for total flow rates of 214 standard centimeters per minute (sccm), the chamber pressure was on the order of 10⁻⁵ Torr. This measurement was taken with an Agilent UHV-24 nude ionization gauge mounted on top of the chamber and corrected for xenon flow using Equation 1.¹⁷

$$P_{corrected} = \frac{(P_{reading} - P_{base})}{2.87} + P_{base} \quad (1)$$

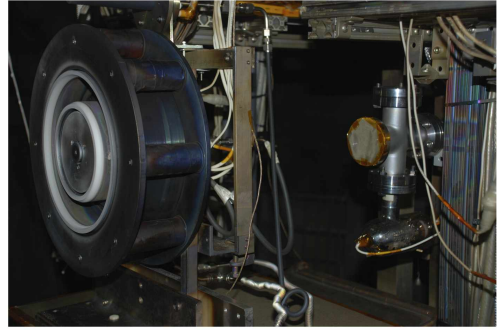
The base pressures measured with this gauge were around 1×10^{-6} Torr during the tests conducted in this study. Pressure measurements were also taken with an internally mounted ion gauge as described in the next subsection.

1. Internal Pressure measurements

In addition to the ionization gauge measuring the pressure at the edge of the chamber, an Agilent 571 external ionization gauge was set up inside the chamber near the thruster to get a better idea of what the pressure was in the chamber near the thruster during thruster operation. The location of the gauge is comparable to the setup described by Diamant with adjustments made for differences in the size of our thrusters (Fig. 1). The opening of the tee facing the thruster was covered in a fine mesh with a 25 micron aperture size, and an open area fraction of 38%. This aperture size was chosen since it was smaller than the estimated Debye length.¹⁸ The other openings of this adapter flange were capped off, and the tee and mesh were isolated from chamber ground. In these experiments, which used flow rates of 20 mg/s in all the operating conditions tested, with a 7% cathode flow fraction (CFF), for total flow rates of 214 sccm, the chamber pressure was around 1.3×10^{-5} Torr, corrected for xenon flow.



(a)



(b)

Figure 1: (a) A picture of the H6 6-kW thruster mounted inside LVTF with a centrally mounted cathode (plus a cathode mounted in a standard external position). In addition, the internal ion gauge is placed several centimeters behind the thruster and slightly to the side of the edge of the thruster. It is also lined up to be roughly along thruster centerline. (b) The internally installed ion gauge was placed behind the thruster mounted on a conflat ‘tee.’ The opening of the tee facing forward, towards the thruster was covered in a fine mesh, the other openings of this adapter flange were capped off.

B. Hall Thruster and Cathodes

The HET used in these tests is a 6-kW Hall thruster, the H6. This laboratory model thruster is one of three identical thrusters built in 2007 through a collaboration between the Air Force Research Laboratory (AFRL), the Plasmadynamics and Electric Propulsion Laboratory (PEPL), and the Jet Propulsion Laboratory (JPL), and serves as a common test-bed for Hall thruster physics research which makes it easier for the three facilities to corroborate research findings, and to coordinate research efforts. This thruster was designed to allow for mounting of a cathode along the center of the thruster. The nominal operating condition for this thruster, which is shown in Fig. 1(a) mounted inside LVTF, is 300 V and 20 mg/s.

The two cathodes used in these experiments were lab-built Lanthanum Hexaboride (LaB_6) hollow cathodes that are based on a JPL-design that sized these cathodes for 20 A which is the nominal operating current for the H6. These cathodes are described in more detail elsewhere.¹⁹

1. Floating the Thruster

All testing was done with the thruster body floating instead of grounded. This more closely simulates thruster conditions when operated in space. Following a setup used by McDonald to isolate the thruster body, first, a few sheets of 0.1 mm thick mica were placed between the thruster's mount and the thrust stand's mounting plate and the thruster was screwed into the mounting plate using fiberglass screws to isolate it from the grounded thrust stand. Also, an electrical line was run from the thruster body to the outside of the chamber, so that we could have control over whether the thruster body was grounded or not.¹⁵

In addition, cryogenic breaks were connected in line with the thruster's flexible metal gas lines so that the thruster did not have an alternate path to ground through these grounded metal gas lines. Cryogenic breaks are segments of metal tubes with a ceramic middle section where the ceramic-to-metal interfaces are hermetically sealed using high temperature vacuum tube-grade braze alloys and provides up to 6 kV of electrical isolation. Lastly, the front of the thrust stand which extended out beyond the thruster's exit plane, and was the closest grounded surface to the downstream region of the thruster, was covered with a sheet of boron nitride sprayed graphoil to decrease the possibility of the thruster arcing to ground through the plume. All of these additions are shown in Fig. 2.

On the air side of the chamber, two circuit options were set up to allow the safe lighting and floating of the thruster. The cable running from the thruster body could be connected to either one. The first circuit grounded the thruster body, and allowed the current to ground to be read into an Agilent DAQ unit, using an F.W. Bell current sensor. Usually we grounded the thruster during lighting since the thruster's start up transients could increase the chance of arcing to ground. The second circuit isolated the thruster body from ground, and allowed the thruster's floating voltage relative to ground to be read into the DAQ. As an added precaution, a bi-directional clamping diode, also known as a transient voltage suppression (TVS) diode, was connected in parallel between the floating line and ground, so that if there were any transients that were too far above or below ground, the diode would short to ground to prevent arcing within the chamber. The particular TVS used has a breakdown voltage of around 68 V and a clamping voltage of 121 V. The breakdown voltage was picked to be about twice what we expected for the thruster body's floating potential.

One thing that is worthy of note is that on a few occasions, the thruster was started while the thruster body was floating, and with this particular set up no arcing between the thruster and ground or cathode spots along the poles were seen.

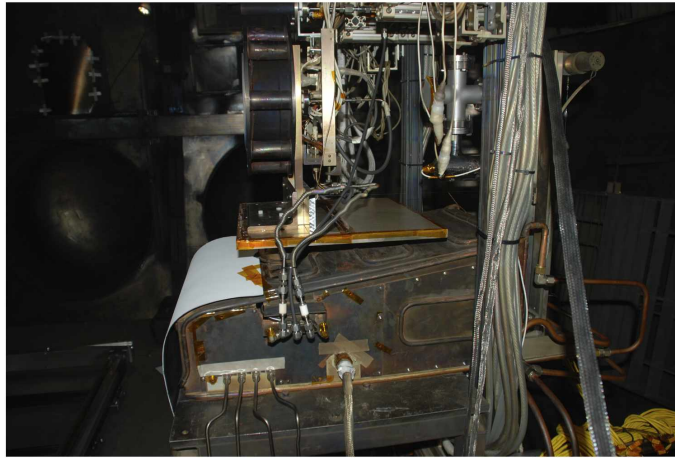


Figure 2: The thruster shown with the various components used to float the thruster body including cryogenic breaks in the metal gas lines, mica sheets between the thruster and thrust stand, fiberglass screws for securing the thruster to the thrust stand mount, and a boron nitride sprayed graphoil flap over the exposed and grounded thrust stand that has a line of sight to the thruster's plume.

C. Cathode's Downstream Positioning & Experimental Setup

The downstream placement of the cathode was governed by two criteria. The first was to keep the cathode inside of the separatrix. In three dimensions, a separatrix is the surface where an equation or vector field switches between different behavioral modes. In this application it refers to the change in the directionality of the magnetic field lines. In past cathode placement experiments, carried out by Sommerville et al.,²⁰ with the cathode placed at a 90° angle relative to thruster centerline, the cathode to ground voltage (V_{c-g}) increased significantly (became less negative) when the electrons were sourced from inside of the separatrix of the thruster's magnetic field relative to when it was outside the separatrix. This larger V_{c-g} signifies a smaller potential difference between the cathode and the beam. Also since Sommerville saw an increase in discharge current along with this increase in V_{c-g} as the cathode was moved inside of the separatrix, this means that the amount of work needed to send the electrons from the cathode to the locations where they were needed in the plume to establish charge neutrality and to complete the circuit was reduced. Figure 3 gives a rough sketch of the H6 B-field lines relative to the general placement of the cathode.

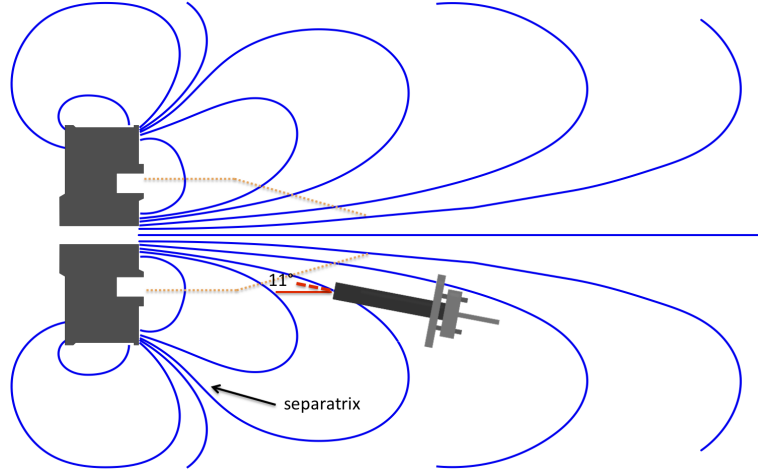


Figure 3: This is a rough sketch of the H6's magnetic field lines showing the placement of the downstream reverse orientation cathode relative to the separatrix and the thruster. The drawing is based on a Magnet simulation of the H6's B-field. **Note: The field lines in this sketch are not exact, nor is the picture to scale with actual H6 dimensions.**

The second specification for downstream cathode placement was keeping the cathode outside of the main part of the ion beam. This was accomplished by using an analysis done by Reid.²¹ A notable portion of the ions in the very near-field region of the thruster have a radial component to their velocity vector, which leads to what he calls "ion beam crossover," meaning that this causes the ions to be focused towards thruster centerline. The radial velocities necessary for the ions to reach centerline at about 1 thruster diameter (D_T) downstream is in keeping with the difference in potential seen between the region in front of the channel and thruster centerline within the first $0.5 D_T$ downstream of the H6's exit plane through plasma potential measurements that were made. This plasma potential difference establishes a radially inward pointing electric field whose aggregate effect on the ions would be strong enough to cause the observed ion beam focusing at about $1 D_T$ downstream. Because of this, the axial location where we searched for the best downstream cathode placement centered around $1 D_T$ from the thruster's exit plane.

Angles less than 90° for the cathode relative to thruster centerline (see Fig. 3) and radial locations that would place the tip of the cathode around channel centerline were explored in the experiments described in this paper. In order to move the cathode around during the test, the cathode was mounted on a theta stage that was then mounted on X-Y tables. The tip of the cathode was centered on the theta stage's axis so that rotating the theta stage would not change the radial and axial location of the location from which electrons were sourced, only the angle. See Fig. 4 for a diagram and Fig. 5 for pictures of the cathode's downstream positioning system. The X and Y linear stages were long enough to allow the cathode to be moved well outside of the range of the thruster during operation of the thruster with the centrally mounted cathode.

Given the previously stated goal of improving HET efficiency by targeting the ionization cost per beam ion and the plasma's ionization fraction in a way that would not require additional power sources or additional

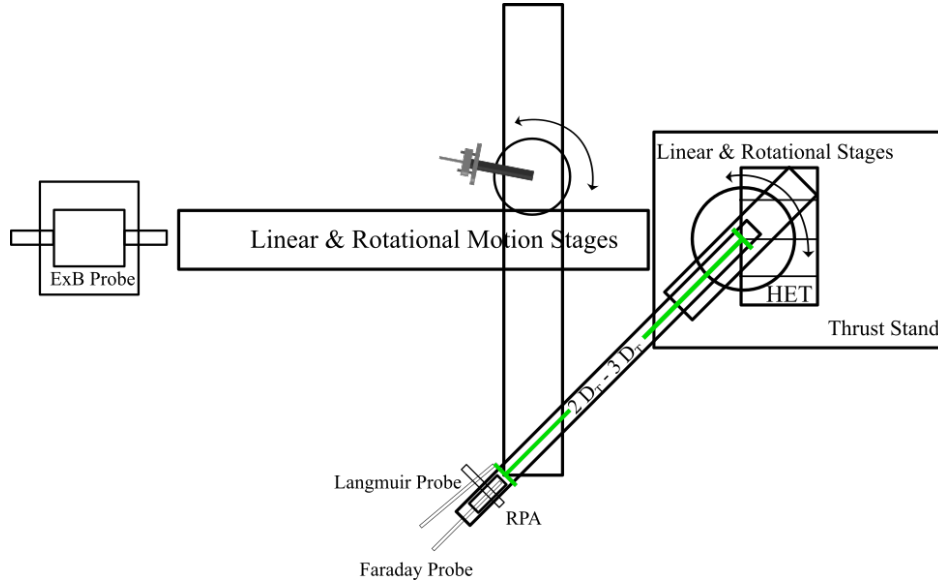


Figure 4: A schematic showing the experimental setup. The cathode was mounted on a rotational stage, which was then mounted on linear stages that could move the cathode in two dimensions. A Faraday probe, RPA and Langmuir probe were mounted on an arm that was secured to a rotational and linear stage so that the angle and radius could be adjusted during the tests. Data was also taken with a thrust stand and ExB probe. This paper will focus on the data obtained with the thrust stand and the RPA.

thruster components so that gains would directly translate into increased efficiency, the intention behind this cathode placement was to allow a more direct path for the electrons to the channel's exit plane where the Hall current, responsible for ionizing gas propellant, is formed. In the initial experiments with the downstream cathode, first the thruster was lit with the centrally mounted cathode with the downstream cathode out of range. Next the external cathode was lit at a 10 sccm flow rate and then slowly moved into position. Then the plume was handed off to the external cathode by slowly decreasing the flow of the central cathode and increasing the flow to the external cathode to a 7% CFF, which was 14 sccm. This process was not ideal since the cathodes dealt with being in such close proximity and nearly facing each other by driving their V_{c-g} well below ground, to around -36 V until the switch off occurred. Therefore, starting the thruster with the external cathode was practiced and perfected.

With a center mounted cathode, the thruster is started while the B-field coil currents are about $2/3$ of their nominal value. With the external cathode, this caused sparking on startup to create the initial electrical connection between the cathode and the thruster, however when the coil currents were decreased to $1/3$ nominal during start up, lighting the thruster with the external cathode was as smooth as lighting with the internal cathode. After start up the B-field was then increased to the desired operating condition, which was the nominal value for the H6 thruster where $B_r/B_r^* = 1$, and is described in more detail elsewhere.²² During external cathode operation, the central cathode (and its keeper) were left floating so that its interaction with the plasma would be minimal.

D. Operating Conditions

The operating conditions that were tested are shown in Tables 1 & 2 and Figures 6 & 7. A 150 V and a 300 V condition were explored for a flow rate of 20 mg/s. This table and figure also show the position of the external cathode that was decided on to explore the effect of a downstream cathode on thruster efficiency. This location was settled on by moving the cathode around and watching the cathode-to-ground voltage, the discharge current, and changes in the null coil current on the thrust stand to get an idea of the overall change in thruster efficiency. Changes in null coil current did not give a definite idea of the thrust value, as the null-current's zero value drifts throughout operation. Therefore, the actual thrust values were not obtained until the thruster was turned off and the thrust value was adjusted with the zero value. This exploration was performed for both the 300 V and the 150 V conditions, so it was not assumed that the same position would

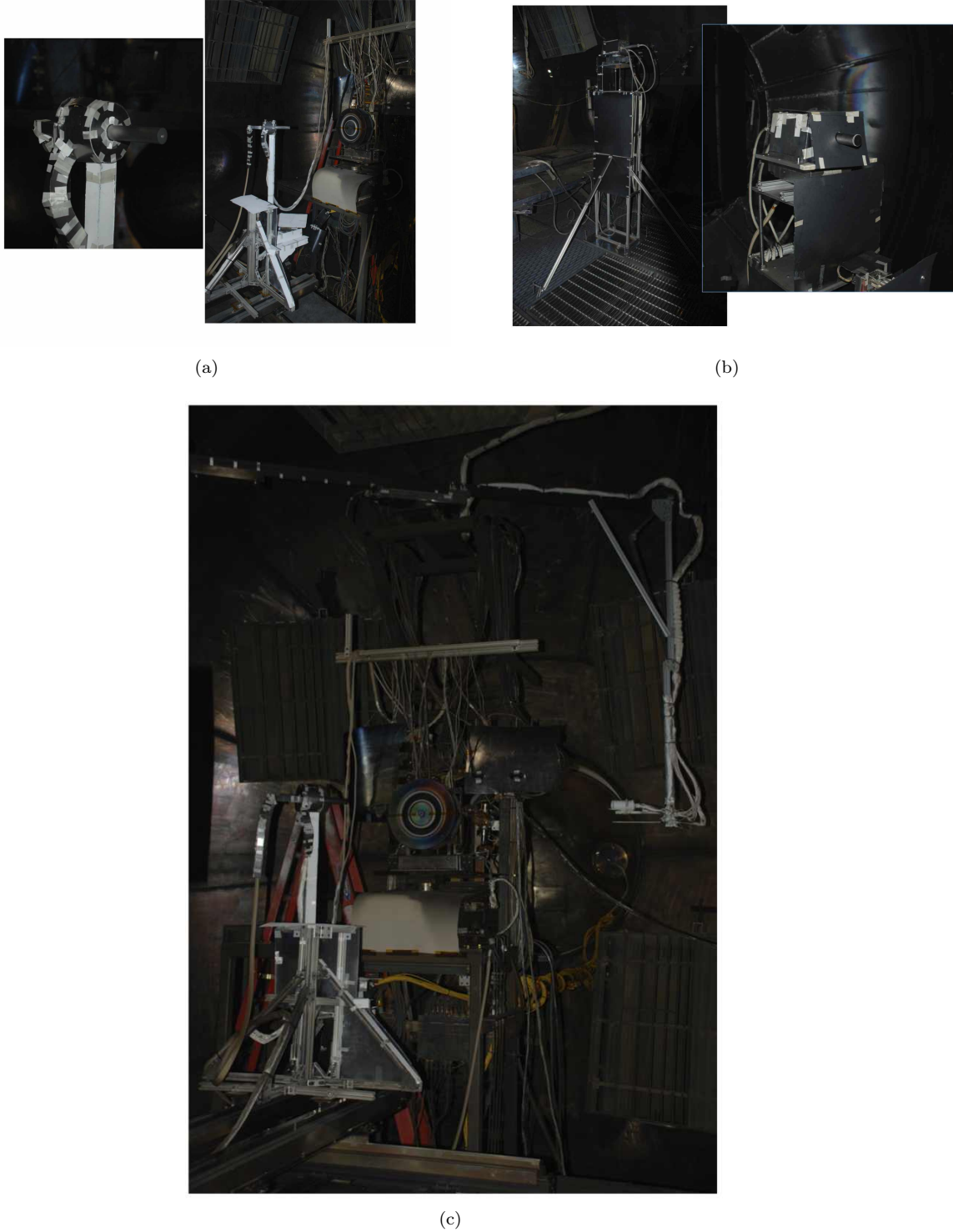
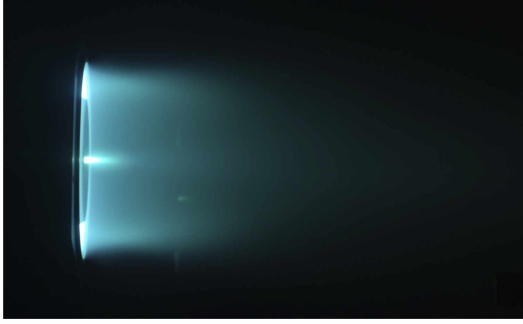


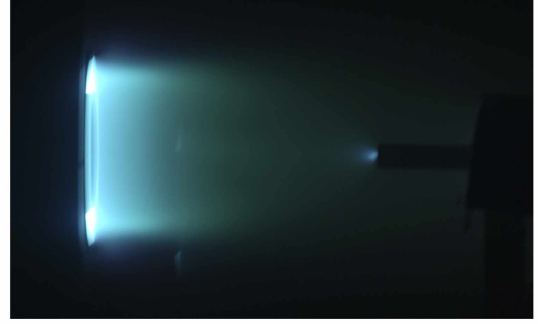
Figure 5: (a) A picture of the external cathode mounted on the X-Y and θ stages, and a close up showing how the cathode and its mount were protected from the plume using graphfoil secured with fiberglass tape. Some of the graphfoil is white because it was sprayed with boron nitride. (b) Close up pictures of the ExB probe and its mounting structure. (c) The full view of the experimental setup which also shows the rotational arm that held the RPA, FP and LP.

Table 1: 300 V 20 mg/s Operating Conditions

$\dot{m}_T$	Cathode orientation	Cathode position	V_D	I_D	V_{keeper}	$V_{f,thruster}$	V_{c-g}
21.4 mg/s	Internal	$\theta = 180^\circ$ $R = 0$ $Z = 0$	300.1 V	17.7 A	2 V	-35 V	-11.1 V
	External	$\theta = 11^\circ$ $R = 1 R_{channel}$ $Z = (15 \setminus 16) D_T$	300.7 V	18.4 A	6 V	-39 V	-8.3 V



(a) Thruster Operating with Internal Cathode



(b) Thruster Operating with External Cathode

Figure 6: 300 V 20 mg/s Operating Conditions

optimize a change in efficiency for both conditions. Thruster discharge current oscillations were monitored throughout testing using a Tektronix TCPA current probe and looking at the signal on an oscilloscope and the same peak-to-peak values and oscillatory behavior were observed between operation with an external and an internal cathode. Changing the B-field strength, and using the trim coil to explore the possibility of further improvements in efficiency with cathode location were outside of the scope of these tests.

E. ExB Probe

The ExB probe, shown in Fig. 5(b), is a velocity selector that uses a balance between the forces of perpendicular electric and magnetic fields on the incoming ion beam to discern the various velocity distributions. The ExB probe consists of three sections which are the entrance collimator, the ExB test section, and the exit collimator. Both the entrance and exit collimators are about 75 mm long. The orifices on both ends of the entrance collimator and at the front end of the exit collimator are all 1.6 mm in diameter. Once the ions pass through the entrance collimator, the beam enters the test section, which is 150 mm long and consists of two metal parallel plates with a 9.41 mm separation gap to which a bias voltage is applied to establish the electric field, and two permanent magnets, which established a magnetic field. The total voltage bias is split around facility ground so that during sweeping of the bias voltage, the center of the test section stays around facility ground to minimize perturbations to plasma external to the probe. As an ion in the collimated beam passes through the test section, its motion is described by the Lorentz equation, which describes the forces on a charged particle due to electric and magnetic fields:

$$\vec{F} = eZ \left(\vec{E} + \vec{v} \times \vec{B} \right). \quad (2)$$

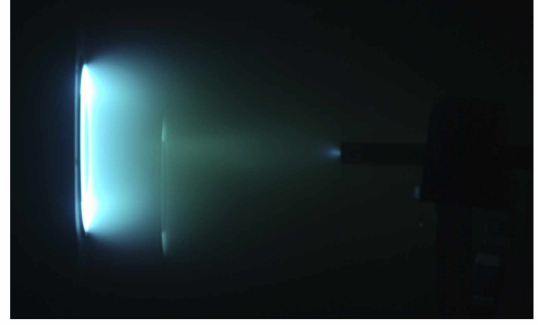
Ions with velocities that allow a balancing of these forces, so that $\vec{F} = 0$ in Equation 2, will pass through the test section undeflected allowing them to continue through the 1.6 mm exit collimator orifice and be

Table 2: 150 V 20 mg/s Operating Conditions

$\dot{m}_T$	Cathode orientation	Cathode position	V_D	I_D	V_{keeper}	$V_{f,thruster}$	V_{c-g}
21.4 mg/s	Internal	$\theta = 180^\circ$ $R = 0$ $Z = 0$	150.4 V	18.9 A	3 V	-24 V	-8.9 V
	External	$\theta = 11^\circ$ $R = 1 R_{channel}$ $Z = (15 \setminus 16) D_T$	150.1 V	19.7 A	5.6 V	-29.5 V	-8.7 V



(a) Thruster Operating with Internal Cathode



(b) Thruster Operating with External Cathode

Figure 7: 150 V 20 mg/s Operating Conditions

collected by the conically shaped collector at the base of the exit collimator section. This high aspect ratio collector, whose shape makes certain that any secondary electron emission (SEE) can be recollected for a net zero current from SEE, is also spray coated with tungsten which has a relatively low SEE yield under xenon bombardment.

Given this design, and the fact that since most of the singly and multiply charged ions are created over a short axial distance—meaning their acceleration voltages are about the same, as the voltage applied to the plates is swept across a range suitable for the thruster and operating conditions being tested, the current collected will form peaked distributions. The probe voltage bias at the peak of each of these distributions can roughly be related back to the ion acceleration potential times its charge state using the following equations:

$$v = -\frac{E}{B} \quad (3a)$$

$$E = -\frac{V_{probe}}{d_{gap}} \quad (3b)$$

$$\langle v \rangle = \sqrt{\frac{2ZeV_{accel}}{M_{Xe}}} \quad (3c)$$

to solve for ZV_{accel} :

$$ZV_{accel} = \left(\frac{V_{probe}}{Bd} \right)^2 \frac{M_{Xe}}{2e}. \quad (4)$$

However, this can only be used to get a rough correlation for this particular probe design because along the 150 mm length of the test section, the magnetic field ranges from 0.097 T at the entrance to a peak value of 0.16 T in the middle. To use Equation 4 most accurately to determine ZV_{accel} from V_{probe} , the probe

would need to be calibrated with an ion source over a range of voltages. This probe was designed by NASA Glenn Research Center (GRC). Further details on its design and setup can found in the literature.^{23, 21}

III. Results and Discussion

A. Overall Efficiency

Table 3: Thrust Results - Cathode Location, Internal vs. External

Cathode Location	V_D	I_D	$\dot{m}_A$	P_{tot}	T	T/P_{tot}
	<i>uncer.</i> ±	<i>uncer.</i> ±	<i>uncer.</i> ±	<i>uncer.</i> ±	<i>uncer.</i> ±	<i>uncer.</i> ±
External	300.7 V	18.44 A	20 mg/s	5.59 kW	404.4 mN	72.3 mN/kW
	±0.1	±0.03	±0.2	±0.008	±0.2	±0.1
Internal	300.1 V	17.70 A	20 mg/s	5.35 kW	385.8 mN	72.1 mN/kW
	±0.1	±0.03	±0.2	±0.008	±0.3	±0.1
External	150.1 V	19.71 A	20 mg/s	3.0 kW	253.9 mN	85.8 mN/kW
	±0.07	±0.03	±0.2	±0.004	±0.2	±0.1
Internal	150.5 V	18.79 A	20 mg/s	2.87 kW	252.0 mN	87.9 mN/kW
	±0.07	±0.03	±0.2	±0.004	±0.2	±0.2

Table 3 shows thrust results for running the H6 with the downstream, reverse orientation cathode (External Cathode) compared to the centrally mounted cathode (Internal Cathode), and Table 4 shows the calculations of total efficiency. Total thruster efficiency was calculated using the following formula:

$$\eta_{tot} = \frac{T^2}{2P_{tot}\dot{m}_T}. \quad (5)$$

Between Internal and External Cathode conditions at 300 V, there is a 3 percentage point increase in efficiency for the same thrust-to-total power. Further details about how the thrust measurements used in these calculations were obtained can be found in a previous paper.²⁴

B. ExB Probe Results

Various methods have been used to analyze ExB probe traces to determine the fraction of each ion species' current. A list of commonly used methods with brief descriptions are listed below:

1. **Peak Heights** - uses the magnitude of the peak heights to describe the relative current of each ion species
2. **Triangle Fitting** - uses a triangle fit to the peak and half-width at half-maximum (HWHM) to estimate the area around each peak to take into account the effect of peak broadening. The HWHM on one side of the curve is chosen for the fit estimate.
3. **Gaussian Fitting** - uses a Gaussian distribution to describe the curve around each visible peak by isolating each of these portions of the total trace and fitting them separately
4. **Variable Exponential Fitting** - similar to Gaussian Fitting, however, in addition, this method allows the exponent for velocity in the exponential function to range anywhere between 2 (a Gaussian distribution in velocity) and 4 (a Druyvesteyn distribution in velocity)

As pointed out in the sources that describe and demonstrate these methods, the issue with all of these approaches is that they do not describe all the space between the distributions, and hence they do not describe the entire ExB probe trace.^{25, 26} It would be advantageous to more fully describe these ExB probe

Table 4: Thruster Efficiency

Cathode Configuration	V_D	I_D	P_{tot}	T	η_{tot}	η_{tot} <i>uncer.</i> $\pm$
Int. Cathode	300.1 V	17.70 A	5.35 kW	385.8 mN	65.0 %	± 0.6
Ext. Cathode	300.7 V	18.44 A	5.59 kW	404.4 mN	68.4 %	± 0.7
Int. Cathode	150.5 V	18.79 A	2.87 kW	252.0 mN	51.7 %	± 0.5
Ext. Cathode	150.1 V	19.71 A	3.00 kW	253.9 mN	50.9 %	± 0.5

traces, which are obtained directly through thruster measurements, for a number of reasons. A few are listed below:

1. The quest to fully understand thruster dynamics is still underway, and if there is additional information already present in the data we collect that could give us further insight into this, then it would be helpful to extract it.
2. When trying to compare different thrusters, operating conditions, or changes in how the thruster is being operated (such as cathode location), fully characterizing the data that is being used to do so in a way that minimizes or eliminates the introduction of biases makes identifying differences in the data an easier, more straightforward task, and increases confidence in the reported results.
3. Further along the lines of the previous reason, finding a method that is as simple, straightforward, and complete as possible, that does not introduce bias into the data and that can be applied to a broad set of data will bring us closer to a standard for analyzing this data that will allow more effective comparison between research papers from various authors and institutions, and between various thrusters or plasma sources. For example, not all plasma sources, operating conditions, or ExB probe placement locations will produce an ExB probe trace that has distinct peaks or that has the same relative broadening of each peak; so, if the analysis method assumes certain things about these elements of the trace, then it will be hard to carry out analysis of some traces and/or compare the results to other traces.

Figure 8 shows the results of a new method for analyzing ExB probe data applied to a trace obtained using the H6 with an internally mounted cathode and taken 2 m downstream from the thruster on thruster centerline. As seen in Fig. 8(a), the entire ExB probe trace is described with a composite Gaussian fit where each Gaussian distribution in the description is of the form:

$$I(V) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(V-V_0)^2}{2\sigma^2}} \quad (6)$$

which is a Druyvesteyn distribution in velocity since voltage $\propto (velocity)^2$, Eq. 3c. This means this distribution $\propto e^{(velocity)^4}$. This is physically accurate because the ExB probe is a velocity selector producing velocity distributions, and a Druyvesteyn function illustrates a steady state distribution of particles in a constant and unvarying electric field with mainly elastic collisions between particles and neutral atoms. Even though there are some inelastic collisions in the plume in the vicinity in front of the probe, such as charge exchange collisions (CEX), there are not enough inelastic collisions, and hence not enough of a transfer of energy from the distribution of particles in question, the ions, to its surroundings, the neutrals, in order for the ions to come into equilibrium with the surroundings. Instead, the ions are in steady state with their surroundings because the inelastic collisions that occur produce a steady, non-zero rate of energy transfer between the system and the surroundings. Another way to state this is that the ions and the neutrals are not the same temperature, therefore they are not in equilibrium, which would be described by a distribution with $e^{(velocity)^2}$ (meaning $\sqrt{voltage}$ would be in the exponential function of the distribution). Figure 8(b) shows the breakdown of the composite fit into the individual distributions that are summed to give fit shown in Fig. 8(a). The R^2 value, the chi-squared value, and the average standard deviation of each point from the fit function, which are statistical indicators of the goodness of fit, are also stated in this figure.

The distributions were picked and summed together in such a way that takes into account the space between the distributions as well. See Fig. 9(a)-(f) for how this was accomplished. First, a distribution

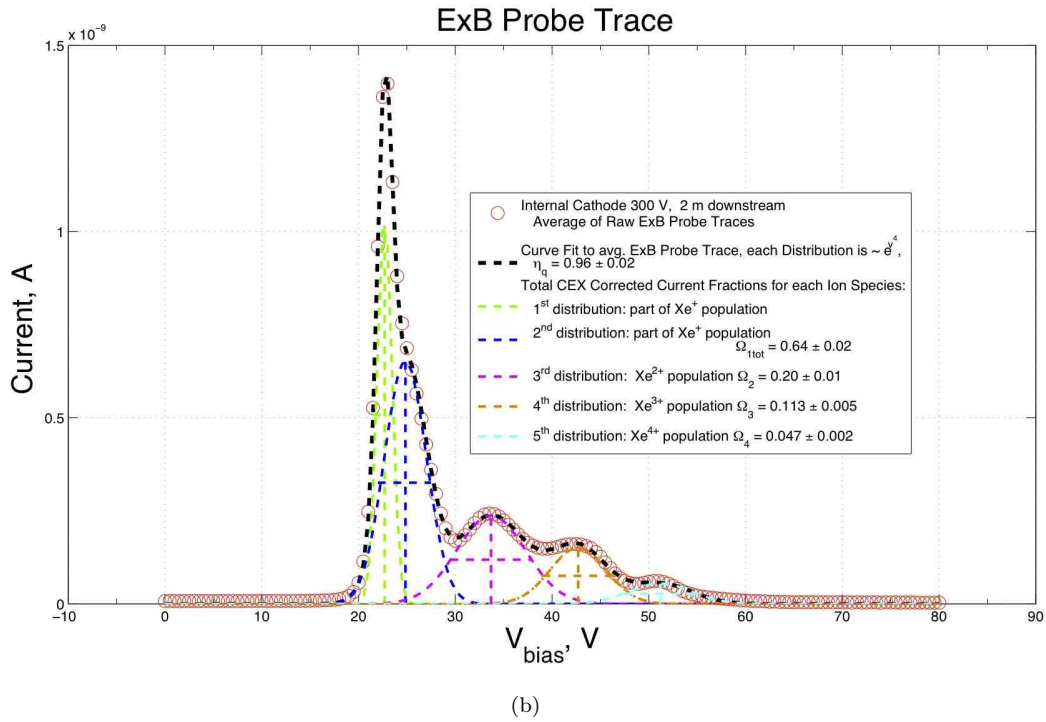
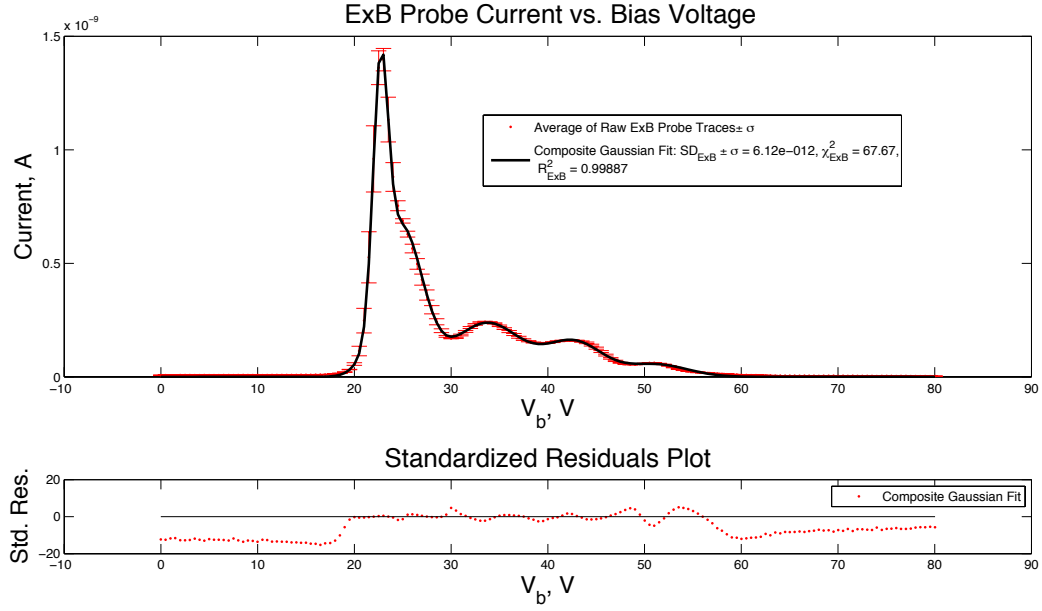


Figure 8: (a) An ExB probe trace 2 m from the thruster's exit plane with the thruster running at 300 V and 20 mg/s with the internal cathode. This graph also shows the total curve fit to the trace, made up of the addition of multiple Druyvesteyn distributions, along with its corresponding chi-squared and R squared values. The standard deviation (SD) of each point from the curve fit is shown with error bars, and the average of these SDs is stated in the legend. (b) The breakdown of the total fit showing each of the Druyvesteyn distributions that are summed to create the curve fit shown in (a).

was fit to each area that looked like it formed a separate distribution, taking into account the neighboring distributions and how their overlap would sum to describe the space between the distributions. This initial fitting, done "by-hand", had to sum to a fit that would be relatively close to the final fit: compare 9(f) to 8(a). Next, this rough fit was fed into a MATLAB chi-squared fitting routine as the initial guess, and the routine came up with the final fit shown in 8. Figure 8(b) also states the CEX corrected current fraction of each ion species, and the resultant charge utilization efficiency. These parameters are found using the following equations:²¹

$$\Omega_i = \frac{I_i}{\sum_{i=1}^N I_i} \quad (7a)$$

$$\eta_q = \frac{\left(\sum_{i=1}^N \Omega_i / \sqrt{Z_i} \right)^2}{\sum_{i=1}^N \Omega_i / \sqrt{Z_i}} \quad (7b)$$

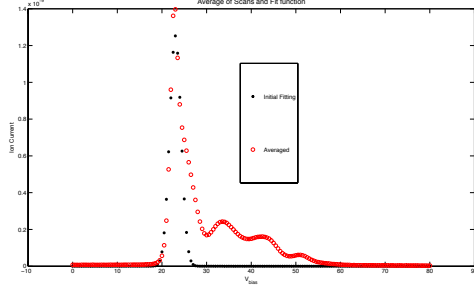
The current fractions, Ω_i , were found by integrating the area under each distribution to find the total current associated with that particular ion charge state. The CEX correction was applied using the method described by Shastry.²⁵ As also seen in Fig. 8(b), the peak representing the singly charged xenon ions is made up of two distinct distributions instead of one. To investigate the possible physical meaning of this, the acceleration voltage associated with the center of these distributions was needed. To get a rough idea of this, the bias voltage at the center of each of these distributions, V_o , and other probe parameters were employed to calculate this value using Eq. 4. The first peak of singly charged ions corresponds to a $V_{accel} \sim 241$ V, which is a little less than the corrected most probable voltage, V_{mp} , obtained with the RPA for this operating condition, ~ 275 V, see reference [24], Table 7. The second peak, which represents a larger portion of the singly ionized xenon population, has a corresponding acceleration potential of ~ 288 V, which is a little more than the corrected V_{mp} , and still much less than double this value. Given these values, these two distributions may represent singly charged ion populations formed by two separate ionization zones, which Haas saw evidence of when he took axial, internal, Langmuir probe measurements along channel centerline using the P5 Hall thruster.²⁷ Perhaps with this more efficient thruster, the H6, the first ionization zone is also very close to the acceleration zone such that the first population of singly charged ions is not mainly lost to the walls as observed by Haas with the P5.

The top of Fig. 10 shows a comparison between the ExB probe trace analyzed in Fig. 8(a) and the trace for the same operating condition and cathode location during the tests that compared running the thruster with the internal and external cathode. For these tests, the ExB probe was further downstream than in the test that produced the data in Fig. 8 due to test setup limitations. However, the same analysis method could be applied to this data, even though all of the peaks are not immediately apparent from glancing at the trace. This analysis, which also includes a noise correction, is shown in figures 11(a) & 12(a), and the current fractions and charge utilization efficiency obtained from these two traces, for this single operating condition are comparable within their uncertainty.

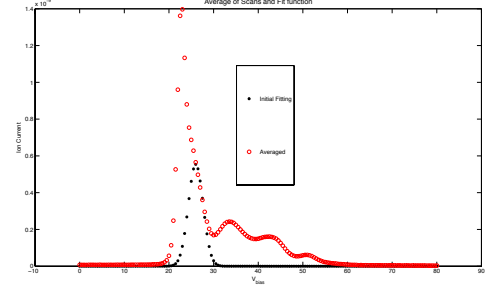
Lastly, the bottom graph in Fig. 10 shows the comparison between the ExB probe traces for the 300 V operating condition for the internal and external cathodes, and figures 11(b) & 12(b) show the analysis for the external cathode case. Even though the total current fraction of singly charged xenon ions is smaller in the external cathode case, it is not enough to make a significant difference in the charge utilization efficiency. Hence, the utilization efficiency remains the same within the propagated uncertainty for the 300 V 20 mg/s operating condition for the external cathode versus the internal cathode. A similar trend is seen for the 150 V condition from figures 13 & 14. A summary of all the ExB probe results, for both the 300 V and 150 V operating conditions, is shown in Table 5.

IV. Summary and Conclusions

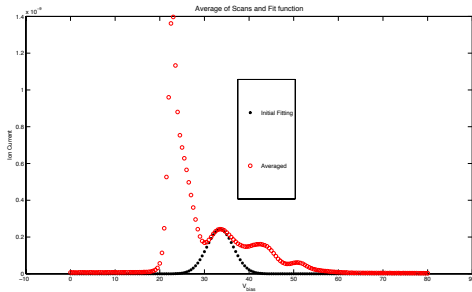
Experiments were carried out to investigate the feasibility and benefit of running a Hall-effect thruster with a downstream reverse orientation cathode. For the 300 V 20 mg/s operating condition, which is the nominal operating condition of the thruster used, the total thruster efficiency increased by a few percentage



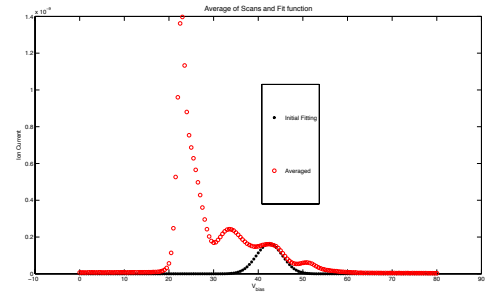
(a) Manual Fit Estimate for the first Distribution



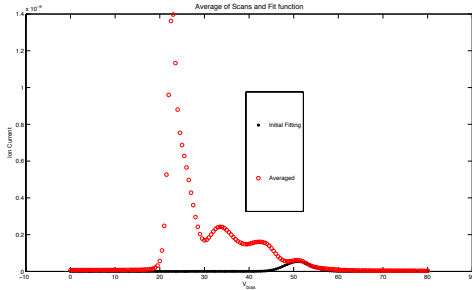
(b) for the Second Distribution



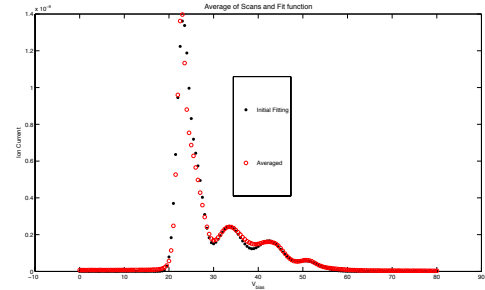
(c) for the Third Distribution



(d) for the Fourth Distribution



(e) for the Fifth Distribution



(f) Summation of all five Distributions

Figure 9: (a)-(e) A series of graphs depicting the steps taken to obtain a fit function estimate that was then used as the starting guess in the chi-squared fitting routine. The guess had to be close enough for this particular routine to obtain a solution. Each hump was fit to a Druyvesteyn distribution taking into account the fact that when the distributions are added together, the space in between the distributions is the sum of the two neighboring distributions that overlap in that area. (f) shows the total estimate and how the space in between the humps can be described by the neighboring distributions.

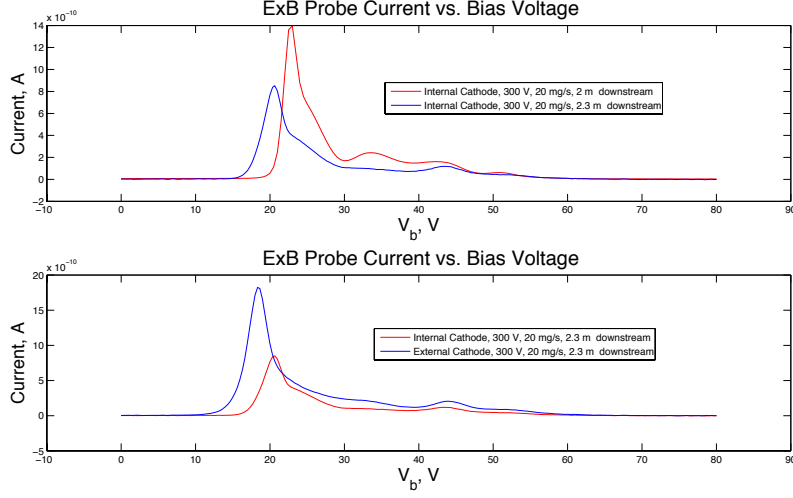
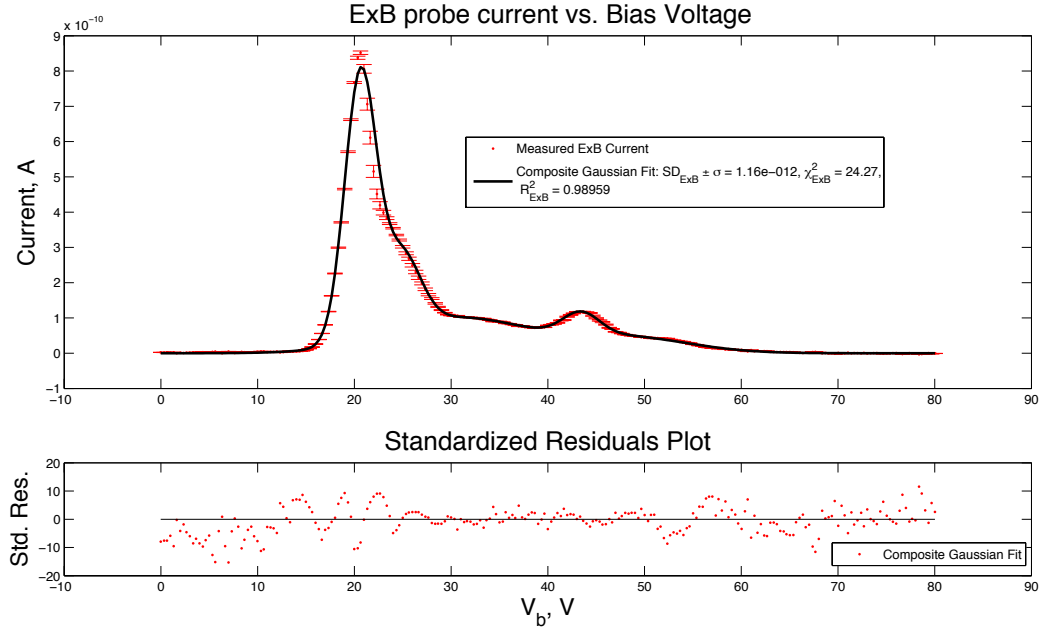


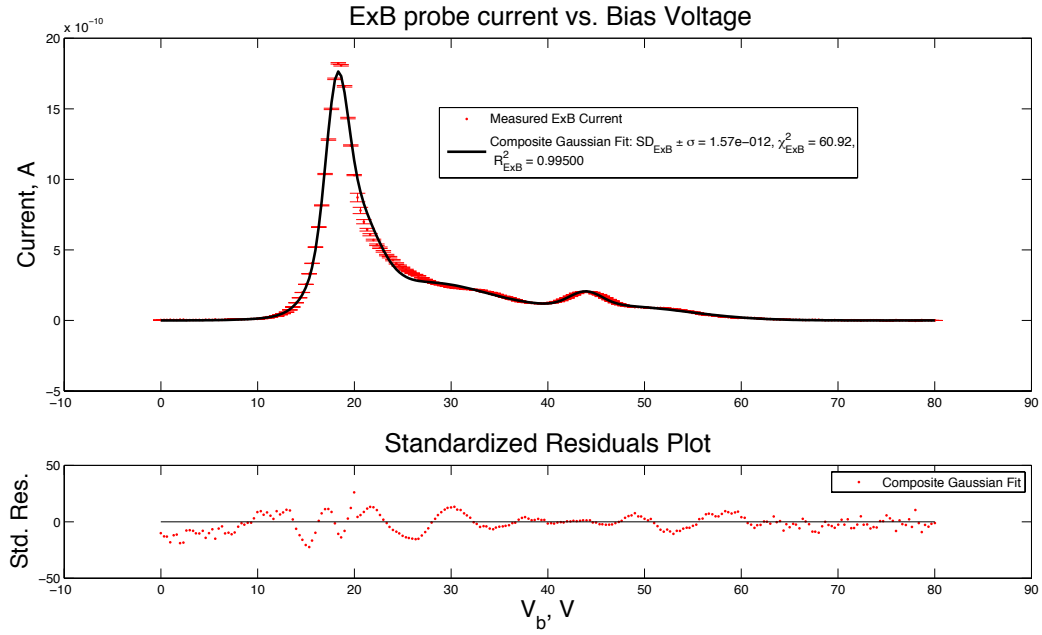
Figure 10: The top graph in this figure shows the ExB probe trace at 2 m downstream (shown separately in Fig. 8(a)) compared to the ExB probe trace 2.3 m downstream (shown by itself in Fig. 11(a)). Both of these traces were taken with the thruster running at 300 V and 20 mg/s. The bottom figure shows a comparison between the probe trace at 2.3 m downstream with the thruster running with the internal cathode versus the external cathode. These two traces are shown separately in Figures 11(a) & 11(b) respectively.

Table 5: Summary of Charge Utilization Efficiency Results - Cathode Location, Internal vs. External

Cathode Location	V_D	I_D	$\dot{m}_A$	P_{tot}	Ω_i <i>uncer.</i> $\pm$	η_{a_q}
	<i>uncer.</i> $\pm$	<i>uncer.</i> $\pm$	<i>uncer.</i> $\pm$	<i>uncer.</i> $\pm$		<i>uncer.</i> $\pm$
External	300.7 V ± 0.1	18.44 A ± 0.03	20 mg/s ± 0.2	5.59 kW ± 0.008	$\Omega_1 = 0.55 \pm 0.02$	0.95
					$\Omega_2 = 0.25 \pm 0.02$	± 0.03
					$\Omega_3 = 0.119 \pm 0.007$	
					$\Omega_4 = 0.082 \pm 0.007$	
Internal	300.1 V ± 0.1	17.70 A ± 0.03	20 mg/s ± 0.2	5.35 kW ± 0.008	$\Omega_1 = 0.62 \pm 0.01$	0.95
					$\Omega_2 = 0.19 \pm 0.01$	± 0.02
					$\Omega_3 = 0.114 \pm 0.004$	
					$\Omega_4 = 0.070 \pm 0.002$	
External	150.1 V ± 0.07	19.71 A ± 0.03	20 mg/s ± 0.2	3.0 kW ± 0.004	$\Omega_1 = 0.68 \pm 0.02$	0.98
					$\Omega_2 = 0.32 \pm 0.02$	± 0.2
Internal	150.5 V ± 0.07	18.79 A ± 0.03	20 mg/s ± 0.2	2.87 kW ± 0.004	$\Omega_1 = 0.74 \pm 0.02$	0.98
					$\Omega_2 = 0.26 \pm 0.02$	± 0.2



(a) Internal Cathode, 300 V and 20 mg/s



(b) External Cathode, 300 V and 20 mg/s

Figure 11: (a) An ExB probe trace 2.3 m from the thruster's exit plane with the thruster running at 300 V and 20 mg/s with the internal cathode. In addition, the total curve fit to the trace is shown, made up by the addition of multiple Druyvesteyn distributions. The legend shows the curve fit's corresponding chi-squared and R squared values. The standard deviation (SD) of each point from the curve fit is shown with error bars, and the average of these SDs is in the legend. (b) The same as (a) but for running the thruster at 300 V with the external cathode.

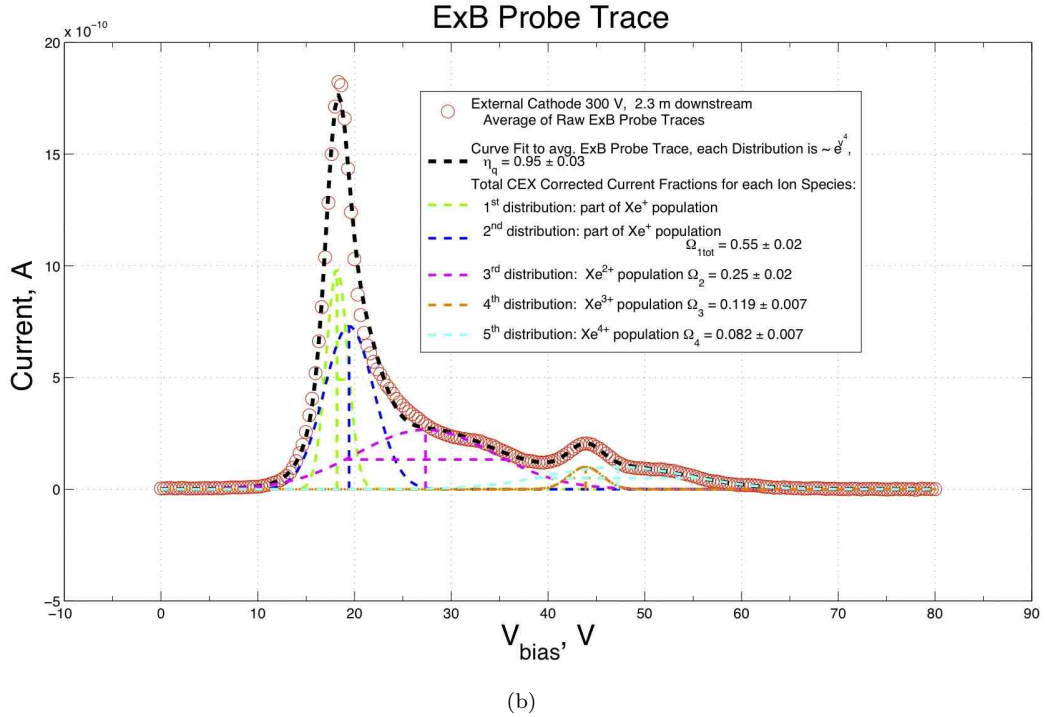
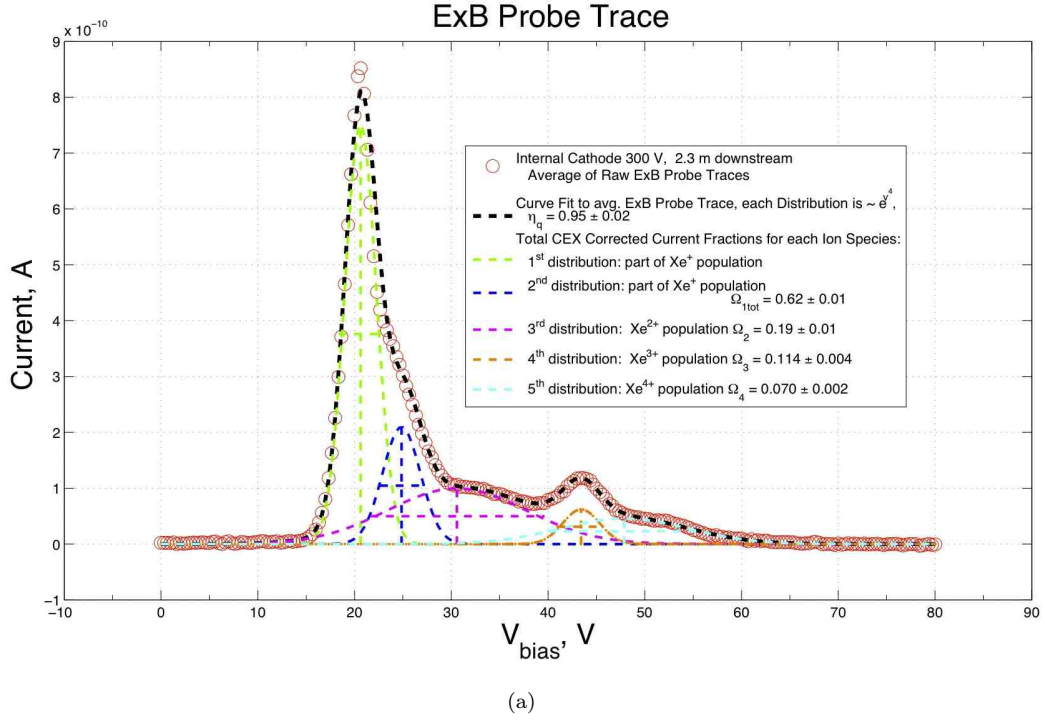
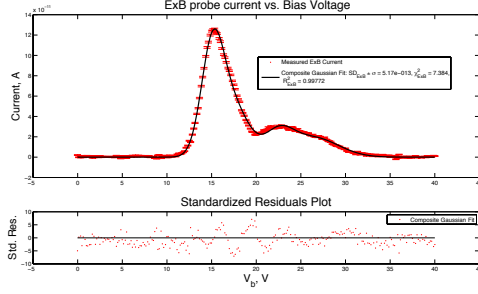
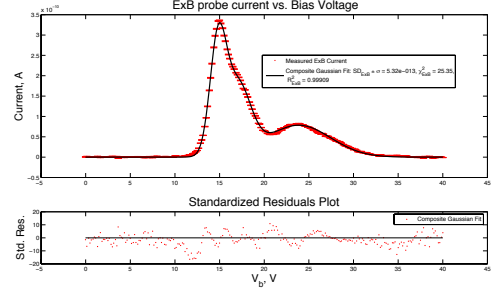


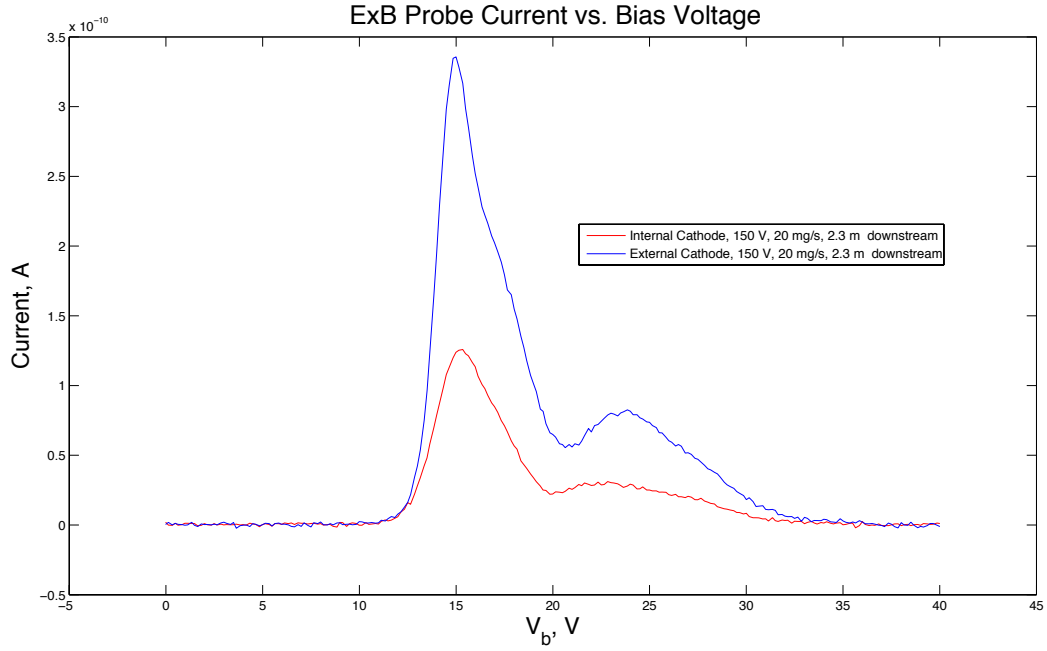
Figure 12: (a) The breakdown of the total fit showing each of the Druyvesteyn distributions that are summed to create the curve fit shown in Fig. 11(a). (b) The breakdown of the total fit showing each of the Druyvesteyn distributions that are summed to create the curve fit shown in Fig. 11(b).



(a) Internal Cathode



(b) External Cathode



(c) Comparison

Figure 13: (a) An ExB probe trace 2.3 m from the thruster's exit plane with the thruster running at 150 V and 20 mg/s with the internal cathode. In addition, the total curve fit to the trace is shown, made up by the addition of multiple Druyvesteyn distributions. The legend shows the curve fit's corresponding chi-squared and R squared values. The standard deviation (SD) of each point from the curve fit is shown with error bars, and the average of these SDs is in the legend. (b) The same as (a) but for running the thruster at 150 V with the external cathode. (c) A comparison between the probe traces taken 2.3 m downstream with the thruster running at 150 V for the internal cathode versus the external cathode.

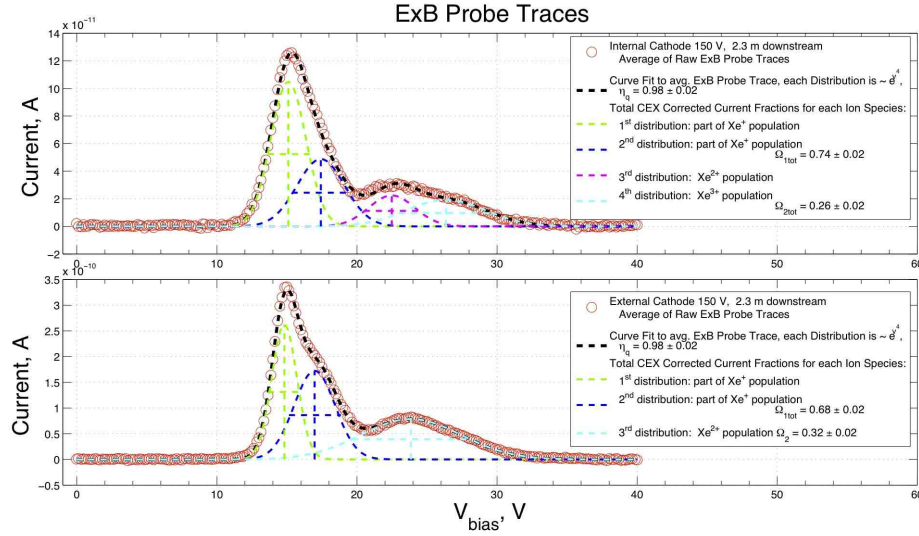


Figure 14: For the 150 V and 20 mg/s operating condition, this graph shows a comparison of the breakdown of the total fit. It depicts each of the Druyvesteyn distributions that are summed to create the curve fits shown in Figures 13(a) & 13(b) for internal and external cathode operation respectively.

points with the downstream cathode compared to the standard case with a centrally mounted cathode. In addition, a new method for analyzing ExB probe data was developed which could more easily be applied to various types of traces. This new method also revealed that the part of the trace representing the singly charged xenon ion population is actually made up of two distinct distributions which is consistent with other Hall thruster investigations using other diagnostics. The ExB probe data showed a higher portion of multiply charged ion species when using a downstream cathode, however the difference was not enough to change the overall charge utilization efficiencies. Hence, these remained about the same within the uncertainty of the calculations for both the 300 V and 150 V operating conditions. The results from this first experiment have set the stage for further experiments and simulations that can look at more precisely determining a downstream cathode location and angle that could have the potential to increase efficiency in the 300 V condition even more. Lessons learned and patterns seen from these experiments can also be used to find better placement of the downstream cathode for the 150 V condition that could lead to increases in total efficiency and thrust for this condition as well.

V. Additional Analysis

Additional data was obtained during the experiments conducted in this paper including thrust stand, Faraday probe, Langmuir probe, and retarding potential analyzer (RPA) data. A previous paper²⁴ can be referenced for voltage utilization efficiency from RPA measurements and further details on total thruster efficiency obtained from thrust stand data. Future papers will discuss divergence, current and mass utilization efficiencies, EEDFs, ionization fraction, ionization cost per beam ion, and erosion estimates for the downstream cathode compared to a centrally mounted cathode. This analysis will give a more complete picture of how the composite total efficiencies presented in this paper for the two cases came about, and will allow discussion of the impact on the downstream reverse orientation cathode EEDF control method on the ionization cost per beam ion. Further recommendations are likely to follow from these results.

Acknowledgments

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