Remote Diagnostic Measurements of Hall Thruster Plumes

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This paper describes measurements of Hall thruster plumes that characterize ion energy distributions and charge state fractions using remotely located plasma diagnostics. Plume measurements were performed using electrostatic analyzers (ESAs) and ExB probes from Plasma Controls, LLC on ion and plasma sources at Colorado State University (CSU) and Hall thrusters operated at the Air Force Institute of Technology (AFIT) and the Air Force Research Laboratory (AFRL). Data are presented from ion source testing at CSU that demonstrated the performance of ESA and ExB probes to characterize energy and charge state. Next, energy and charge state measurements are described from testing of a 200 W Hall thruster at AFIT. Measurements showed variation in the ion energy distribution with changes in thruster power and an increase in the fractions of multiply charged ions with increasing azimuthal position. Finally, ExB probe charge state measurements are presented from a 6 kW class laboratory Hall thruster operated at low discharge voltage levels at AFRL/RZSS. Like the 200 W Hall thruster measurements at AFIT, results from the 6 kW Hall thruster showed an increase in the fractions of multiply charged ions with increasing azimuthal position.

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Nomenclature

AFIT	=	Air Force Institute of Technology
AFRL	=	Air Force Research Laboratory
B	=	magnetic field strength
CSU	=	Colorado State University
d	=	plate separation distance
ESA	=	electrostatic analyzer
E	=	energy or electric field
ExB	=	Electric field crossed with magnetic field
ϕ	=	plate voltage
IEDF	=	ion energy distribution function
q	=	ion/electron charge
m	=	mass of given ion
r	=	radius
v	=	velocity
V	=	voltage/potential
z	=	ion charge state (1,2,3, etc.)

I. Introduction

ELECTRIC propulsion devices, such as ion thrusters and Hall thrusters, have functional applications in space for primary and auxiliary propulsion of satellites, with over 100 satellites currently employing electric propulsion devices [Goebel and Katz[1] 2008; Tighe et al.[2] 2008; Hofer et al.[3] 2006]. As part of increasing the application and performance capabilities of these EP devices, characterizing the plasma plume is both useful and necessary, such as for calculating thrust parameters (thrust direction, plume divergence) and determining possible plume interactions with nearby satellite components. Important plume parameters of interest include the ion energy distribution function (IEDF) along with charge state measurements for accurate characterization of ion exhaust velocities. It is of further use if this data can be obtained in a spatially resolved manner to yield information about thrust direction. The measurements and diagnostics described in this paper are useful for characterizing specific thruster models as well as for validating/improving numerical models such as COLISEUM which predict plasma/spacecraft interactions [Niemela[4] 2006].

II. Diagnostics

We first describe the details and method of operation for two remotely located plasma probes: an electrostatic analyzer (ESA) and ExB probe. Then, each facility is described along with applicable testing and results from the plasma diagnostics. Three facilities are described that include plasma measurements of 1) ion and plasma sources operated at the CEPPE lab at Colorado State University (CSU), 2) a 200 W Hall thruster operated the Air Force Institute of Technology (AFIT), and 3) a 6 kW laboratory model Hall thruster operated at the Air Force Research Laboratory (AFRL), Edwards, AFB.

A. Electrostatic Analyzer (ESA)

An electrostatic analyzer is a diagnostic tool that can be used to measure ion energy distributions of plasma devices. The ESAs used in the studies of this paper are manufactured by Plasma Controls, LLC for specific use in the plume of plasma devices such as ion and Hall thrusters. A schematic and picture of the ESA is shown in Figure 1. The approximate dimensions of the probe are 10.8 cm deep by 18.3 cm wide by 5.0 cm high. The main components of the ESA are the body housing, collimators, segments, and the collector apparatus. The stainless steel housing is used to shield out unwanted plasma and to mount the probe apparatus. The energy-to-charge state ratio selection is accomplished by electrically biasing two spherical segments that are fabricated in a 120 degree arc [Moore et al.[5] 2002; Farnell[6] 2007]. The field of view of the device is limited by an entrance and exit collimator placed at each end of the spherical segments. The collimators are designed to produce an acceptance angle of ±2.5 degrees. The collector plate is located at the downstream end of the exit collimator. The calculated resolution of the ESA is approximately $\Delta E/E_{trans} = 0.015$.

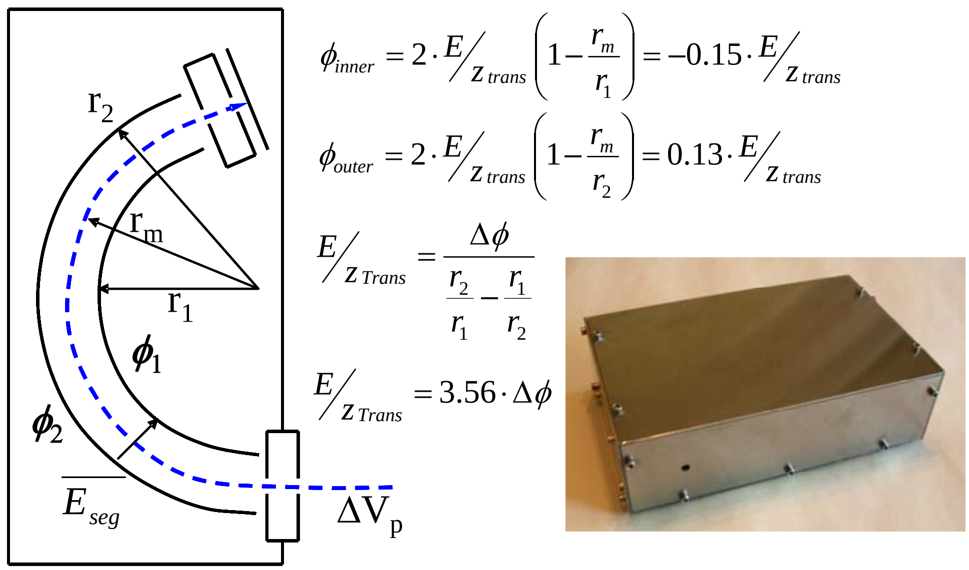

Figure 1. ESA electrical schematic and picture.

The electrostatic analyzer is designed to separate ions according to their energy-to-charge ratio (E/z). This is done by applying voltage biases to two spherically nested segments so that ions entering the probe feel an electrostatic force. The velocity, v, of an ion entering the ESA (neglecting initial thermal velocities), can be described in terms of ion energy by:

$$E = z \cdot q \cdot \Delta V_p = \frac{1}{2} \cdot m \cdot v^2 \quad \text{or} \quad v = \sqrt{\frac{2 \cdot z \cdot q \cdot \Delta V_p}{m}} \qquad (1)$$

Where E is ion energy, z is charge state, q is electronic charge, m is ion mass, and ΔV_p is a potential difference between the ion creation point in the plasma and the entrance collimator of the ESA. Solving these equations in spherical coordinates for the electrostatic force due to the ESA segments gives a relation between the plasma potential difference and the plate voltages on the ESA, $\Delta\phi$:

$$\Delta V_p = \frac{\Delta\phi}{\frac{r_2}{r_1} - \frac{r_1}{r_2}} = 3.56 \cdot \Delta\phi \qquad (2)$$

Note that the charge state, z, and mass, m, cancel out of the equation, thus the ESA does not differentiate between different ion species. Also, the ESA detects only the energy-to-charge ratio, E/z, so that a singly charged ion and a doubly charged ion that go through the same potential difference ΔV_p are measured at the same segment voltage difference, $\Delta\phi$. The constant transmission mode of operation is generally preferred to obtain the ion energy distribution function (IEDF). This mode works by applying a constant $\Delta\phi$ between the spherical segments and sweeping the entrance and exit collimators (along with the spherical segments) with respect to the vacuum facility ground. The current to the collector plate is recorded as a function of the bias voltages, which determines the selected ion energy-to-charge ratio (E/z).

B. Diagnostic - ExB Probe

Another useful device in measuring properties of plasma plumes is the ExB probe (or Wein filter), which has the ability to separate ions according to their energy (E), mass (m), and charge state (z) [Moore et al.[5] 2002; Farnell[6] 2007; Vahrenkamp[7] 1973; Hofer and Gallimore[8] 2003]. The ExB probe utilizes a magnetic field placed normal to the axis of an electric field to separate ions. The ExB probes utilized in this paper were manufactured by Plasma Controls, LLC. The approximate dimensions of the probe are 27.0 cm deep by 6.9 cm wide by 4.7 cm high. The main components of the ExB probe are the body housing, entrance collimator, ExB separator section, drift tube, and the collector apparatus. The stainless steel housing is used to shield out unwanted plasma. The entrance to the probe is equipped with a small orifice diameter collimator designed to give a narrow acceptance angle of ±0.30 degrees.

The ExB section is where the electric and magnetic fields are applied to separate the ions. The collector plate is located at the downstream end of the drift tube.

A diagram of the ExB probe is shown in Figure 2. Ions that are able to pass through the entrance collimator enter the separation region where the ions feel a force from both electric and magnetic fields according to the Lorentz force equation:

$$\overline{F} = q \cdot (\overline{E} + \overline{v} \times \overline{B}) \tag{3}$$

F is the force on the ion, q is the electronic charge, E is the electric field strength, v is the ion velocity, and B is the magnetic field strength.

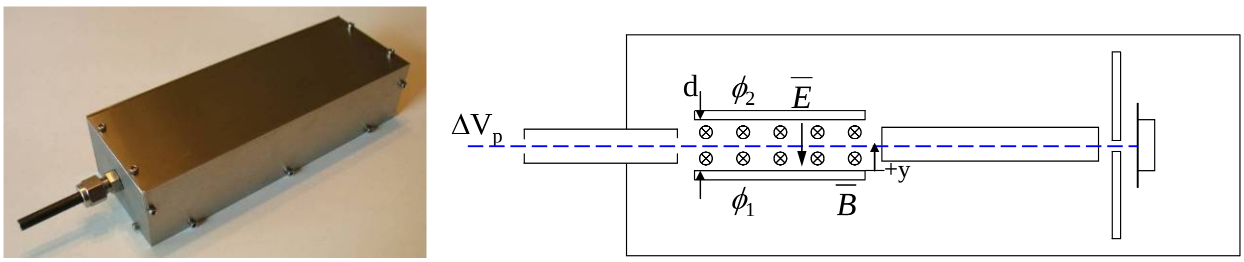

Figure 2. ExB probe schematic showing the electric field and magnetic field separation section. The amount of direction change the ion undergoes depends on its entrance energy and the applied electric and magnetic field strengths.

In order to pass through the probe to the collector plate, the net force on an ion must be (near) zero so that the ion is not pushed off the drift axis. Setting the force equal to zero and rearranging the equation yields:

$$\overline{E} = -\overline{v} \times \overline{B} \tag{4}$$

Inserting equations for the electric field and velocity, the resulting equation for the ions that are measured by the probe is:

$$\Delta\phi = B \cdot d \cdot \sqrt{\frac{2 \cdot z \cdot q \cdot \Delta V_p}{m}} \tag{5}$$

Where $\Delta\phi$ is the voltage difference between the plates, B is the magnetic field strength, d is the separation distance between the plates, and all other parameters are the same as defined previously.

When taking measurements, the plate voltage difference, $\Delta\phi$, is swept while recording the current to the collector plate. The magnetic field, B, is produced using a permanent magnet. The plate separation distance and the magnetic field are constant, such that each ion is separated according to the mass, m, charge state, z, and the potential difference between the ion creation point in the plasma and the entrance collimator of the ExB, ΔV_p.

III. Facilities and Test Results

C. Colorado State University CEPPE Lab (CSU)

At Colorado State University (CSU), ESA and ExB measurements were performed on two ion sources. The first ion source was an 8 cm diameter, filament ion source that could be operated on a combination of argon and xenon gases. The second ion source was one that was operated on argon as well as bismuth to produce bismuth metal propellant ions. These arrangements were chosen to verify both the operation of the ESA with respect to ion energy as well as the ExB probe with respect to differentiation of ion mass and charge state.

1. CSU Source 1 – Argon/Xenon Ion Source

The first CSU ion source setup is shown in Figure 3 with an 8 cm ion source mounted vertically at the top of a vacuum chamber. The ESA and ExB probes were mounted separately in the downstream centerline plume region of the source at a distance of 30 cm from the ion optics.

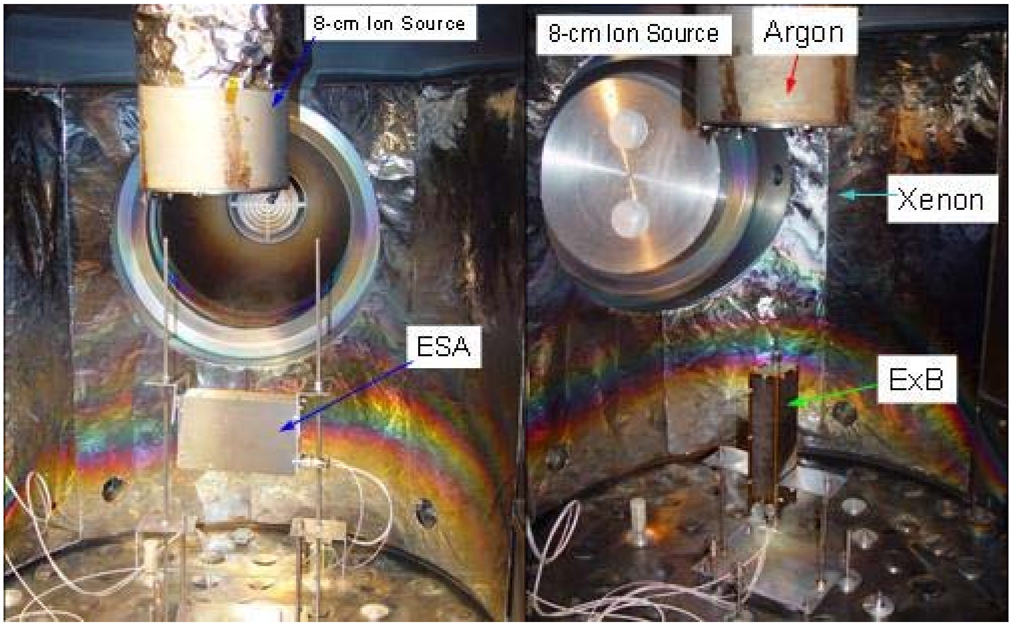

Figure 3. Setup of the ESA (left picture) and ExB (right picture) relative to an 8 cm diameter ion source.

To test the characteristics of the ESA, the ion source was operated on argon gas at selected beam voltages of 250, 400, and 550 V. The beam current was held constant at 40 mA and the pressure in the vacuum chamber was 1.9×10^{-5} Torr. The segment potentials on the ESA were set to transmit ions with energy-to-charge ratios (E/z) equal to 300 eV ($\Delta V_{segments}$ = 84.4 V). With the transmission energy of the ESA set to a constant value, the probe voltages were swept over a wide voltage range to record the ion energy distribution (E/z). At each of the selected beam voltages, the ESA IEDFs indicated peak current magnitude ion energies that were a few volts (5 to 10 eV) below the set beam voltage on the ion source power supply (Figure 4). Since the peak energy was not exactly equal to the beam voltage set point, two reasons may be briefly considered. First, it is reasonable to think that the peak energies of the ion beam were not equal to the set beam voltage, either from differences in applied voltages to the ion source or plasma discharge voltages that were below the discharge voltage. The second reason might be that the ESA was not giving proper measurements due to slight probe error. The second concern can be addressed by observing the locations of the energy peaks on other ion sources and thrusters presented in this paper, which show the measured peak of the IEDFs occurring at or slightly above the voltage set points. The evidence of consistent energy readings relative to beam voltages over a wide range of plasma devices gives confidence in the correctness of the probe theory, assembly, and measurements.

For testing of the ExB probe, the ion source was operated on multiple gases to demonstrate the ability to differentiate ion mass constituents as well as charge state fractions. Argon gas was fed directly into the ion source discharge chamber while additional xenon gas was separately injected into the vacuum chamber as backflow. The xenon gas backflow was sufficient to allow some of xenon gas to be ingested into and ionized within the ion source. Figure 5 shows the measurements from the ExB probe with the ion source beam voltage set to 550 V. Signals of both xenon (131.3 amu) and argon (39.95 amu) were seen for both singly and doubly charged ions. In addition, small amounts of nitrogen (N_2) were ionized in the source when measurements were made shortly after crossover to high vacuum.

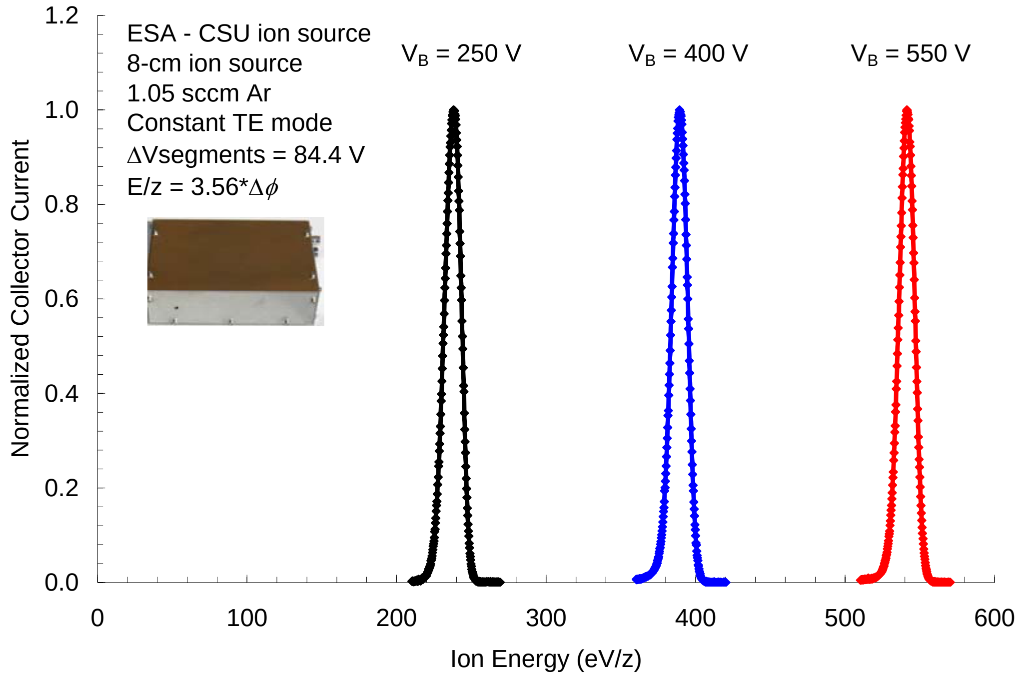

Figure 4. Data taken with the ESA for argon ions originating from an 8 cm diameter ion source at CSU. The peak of the distributions occurred a few eV lower than the ion source power supply set point.

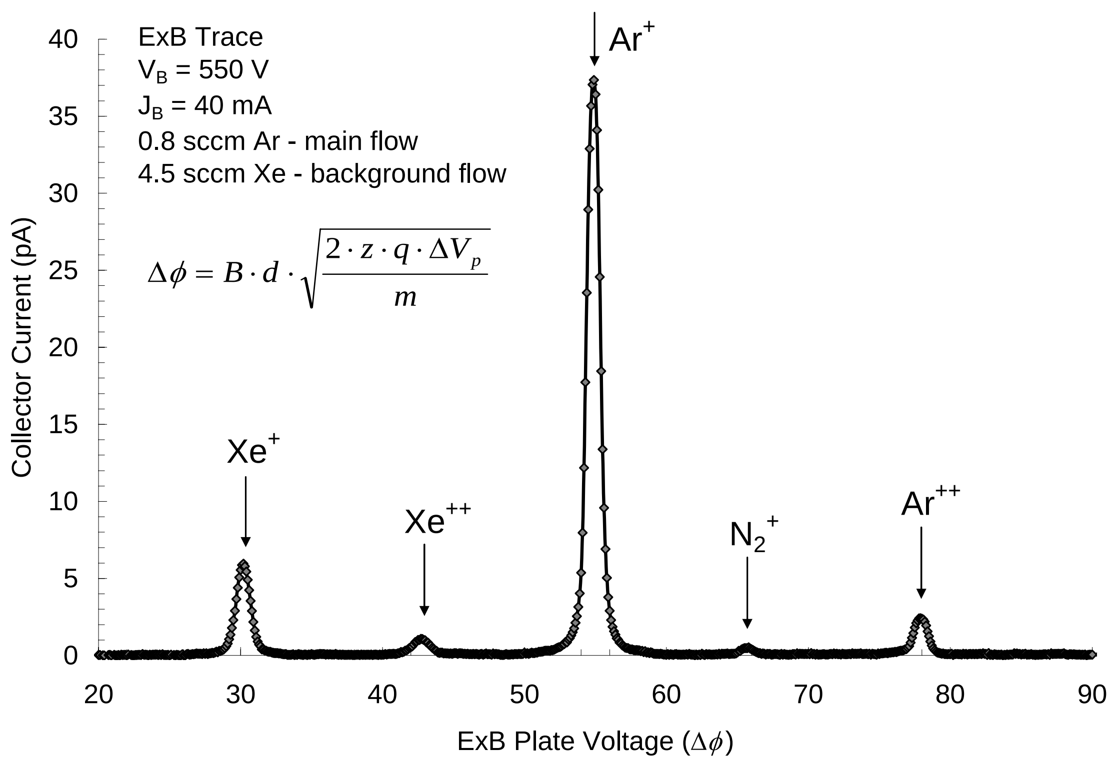

Figure 5. Data taken with the ExB probe of argon and xenon ions from an 8 cm diameter ion source at CSU.

2. CSU Source 2 – Argon/Bismuth Ion Source

The second setup at CSU involved the ESA and ExB probes placed 15 cm downstream of a filament ion source operated on argon and bismuth metal propellant [Wilbur and Wei[9] 1992]. The ESA was used to measure IEDFs at three beam voltages of 200, 250, and 300 V, shown in Figure 6. In each case, the energy at the peak current magnitude of the distribution was a few eV above the beam voltage set point. The data of Figure 6 compare favorably with ion energy results from the other CSU ion source tested (CSU source 1) and Hall thruster measurements from the other facilities.

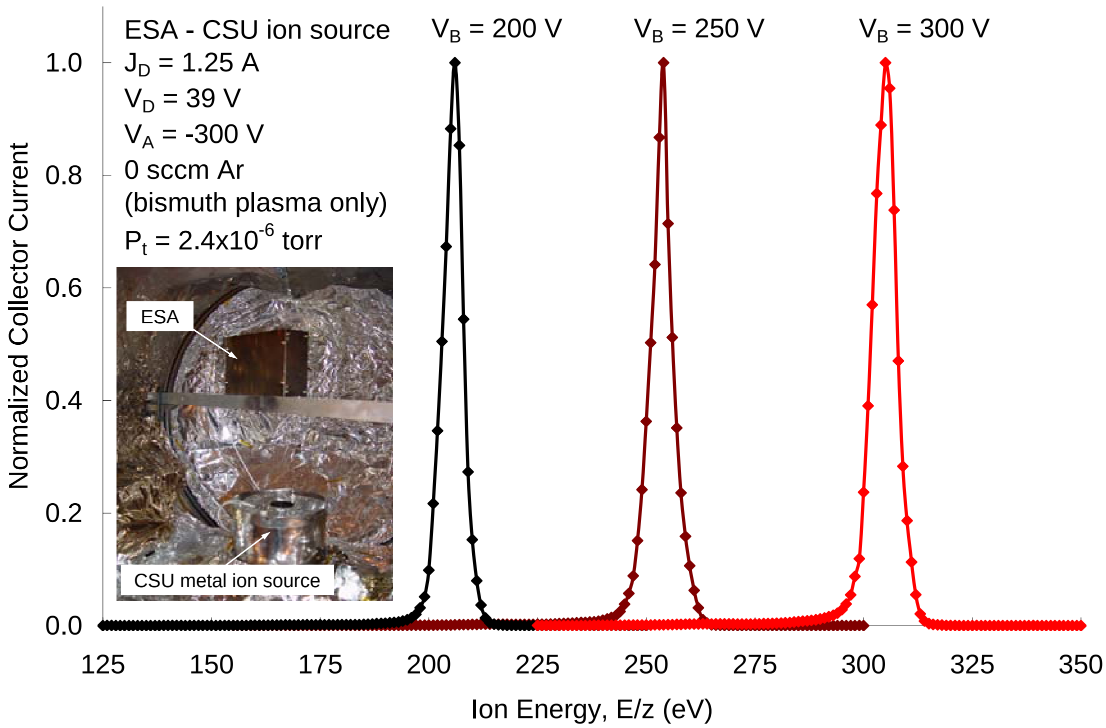

Figure 6. IEDFs of ions produced within a CSU metal ion source. The ion source was operated on bismuth propellant at beam voltages of 200, 250, and 300V.

The ExB probe was used to measure ions that were produced from the source, as shown in Figure 7. The beam voltage was set to 300 V while argon and bismuth plasma was produced by flowing argon at 2.0 sccm and heating bismuth metal to produce bismuth vapor inside the discharge chamber. With this operating condition, both argon and bismuth ions were produced with most of the ions being singly charged (Ar^+ and Bi^+). There were also doubly charged ions of each constituent along with a small signal of triply charged bismuth. Interestingly, a number of Bi_2^+ ions were also formed in the discharge plasma. Some nitrogen (N_2^+) and water (H_2O^+) ions were seen as well due to a small air leak in the argon flow system and residual water in the ion source. The water signal decreased as the source was operated over a span of tens of minutes.

D. Air Force Institute of Technology (AFIT)

Testing of a 200 W Hall thruster was performed at the Air Force Institute of Technology (AFIT) in the Space Propulsion Analysis and System Simulator (SPASS) Lab, at Wright-Patterson Air Force Base. Figure 8 shows a picture of the Hall thruster and probe positioning system within the vacuum chamber. The Hall thruster was operated at three power conditions on xenon gas: at a nominal 200 W power level (condition A), at a lower 150 W power level (condition B), and at a higher 250 W power level (condition C). The ESA and ExB probes were separately mounted to a three-axis positioning system that could move the probes within the downstream plume region of the Hall thruster. Two linear stages were used for translational movement in the r-z directions (1m by 1m travel) and a third motor (theta rotation) was used for rotational movement to point the probes along desired sight lines. The vacuum chamber interior measured 2.54 meters in length and 1.80 meters in diameter. During operation of the Hall thruster, with xenon flowing, chamber pressure typically ranged from 1x10^{-6} to 1x10^{-5} Torr.

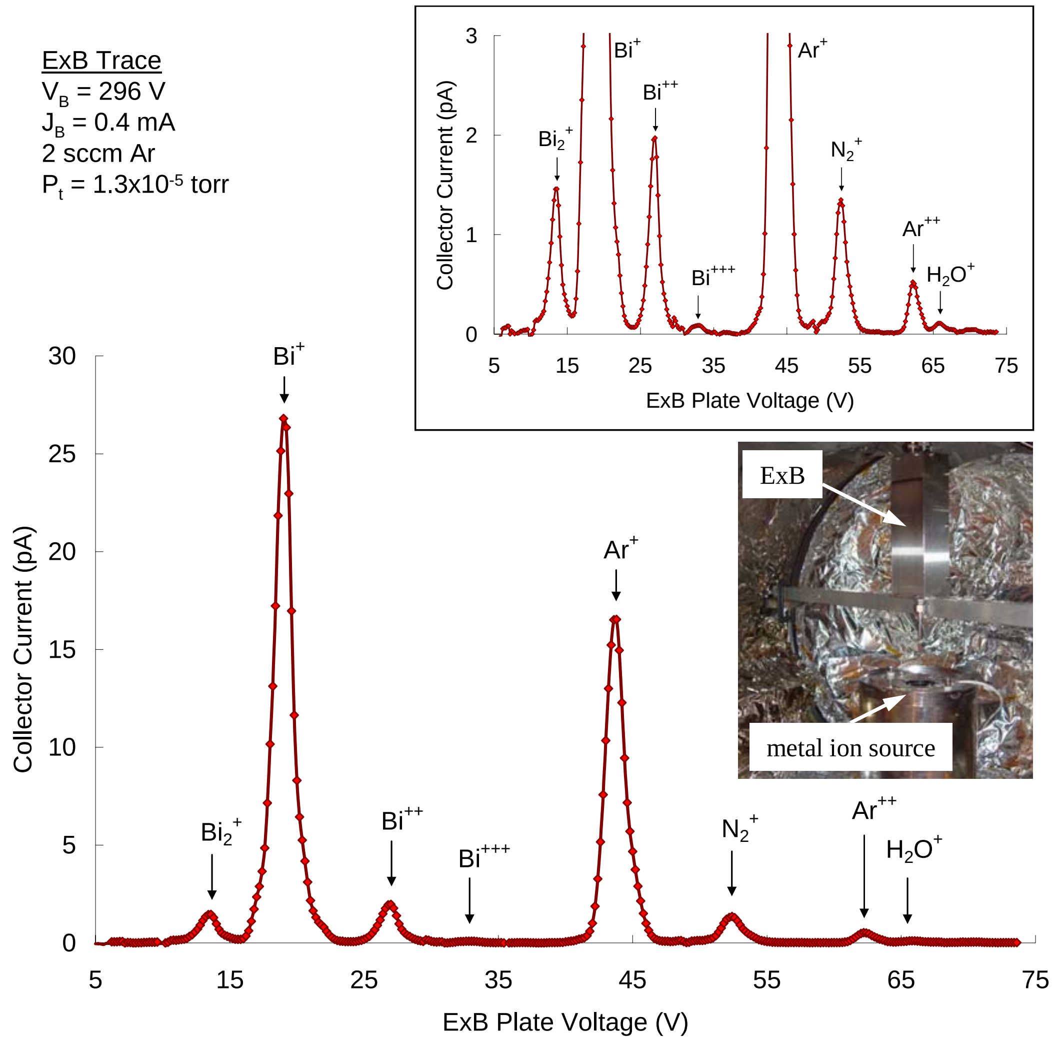

Figure 7. ExB measurement of ions produced within a CSU metal ion source. The source was operated on a combination of argon and bismuth propellants. Inset shows data on expanded y-axis to show the Bi^{+3} peak.

Condition	B	A	C
Power Setting (W)	150	200	250
Discharge Voltage, V_D (V)	186	248	294
Discharge Current, J_D (A)	0.80	0.78	0.86
Main Flow (sccm Xe)	0.84	0.84	0.84
Cathode Flow (sccm Xe)	0.07	0.07	0.07
Magnet Current (A)	1.50	1.50	1.95

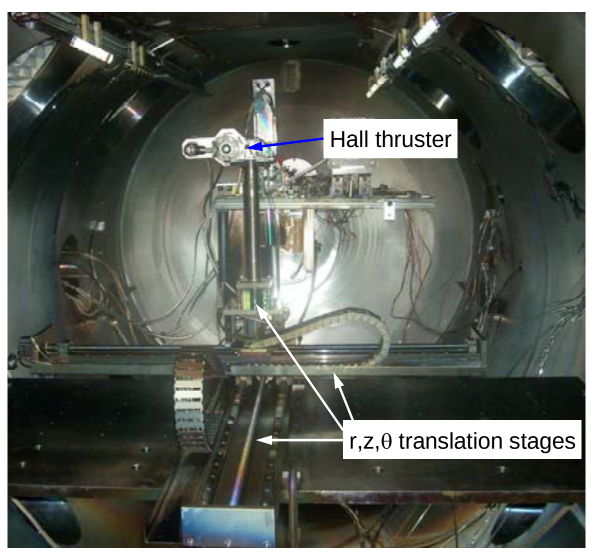

Figure 8. Setup of the 200 W Hall thruster and probe positioning system at the AFIT facility.

The ESA was positioned at a constant spherical distance of 57 cm from the Hall thruster. The ESA was rotated azimuthally to point at angles of 0, 15, 30, 45, and 80 degrees relative to the thruster centerline axis. High resolution ESA sweeps were performed at each location and the results are shown in Figure 9 for operating conditions A, B, and C. As expected, the largest ion signals were seen along the thruster centerline axis at 0 degrees with ions having energies from 100 to 300 eV. As the power (anode voltage/current) was increased from condition A to condition C, the energy of the ions increased with the peak of the ion energy distributions matching the discharge voltage. At off axis angles, there was evidence of a low energy shoulder having energies from 50 to 150 eV below the peak ion energies. The low energy shoulder became more prominent as the power/discharge voltage was increased from condition A to condition C. The IEDFs at the nominal 200 W condition (condition A) compare well with measurements made by Beal[10] [2003] using ESA and RPA probes. Looking at the energy distribution taken at a wide azimuthal angle of 80 degrees (condition A inset), the energy distribution was broad with a peak at 55 eV and a tail extending to 200 eV. At the 80 degree angle, the peak current magnitudes were roughly 2% of the peak centerline currents.

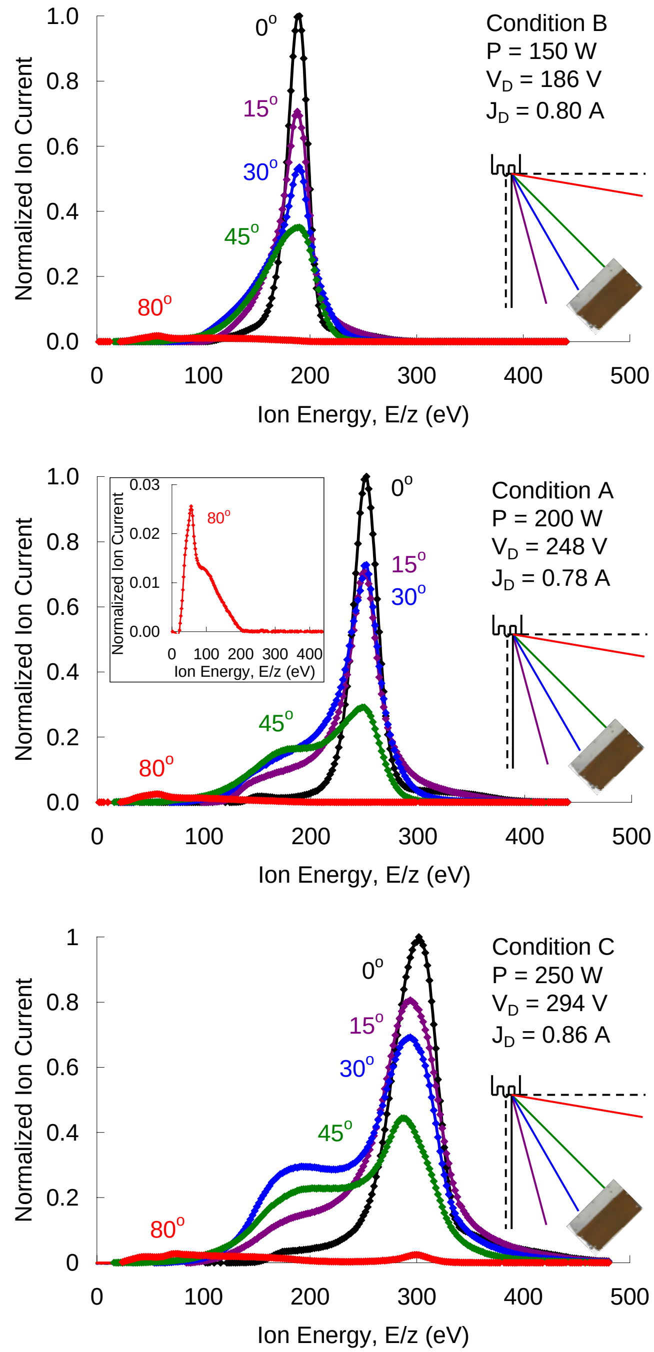

Figure 9. IEDFs measured using the ESA at power levels of 150, 200, and 250 W.

Like the ESA, the ExB probe was mounted to the positioning system and charge state measurements were made at selected azimuthal locations of 0, 15, 30, 45, and 60 degrees at a constant spherical distance of 57 cm from the thruster. To compare the ion fractions of singly, doubly, and triply charged ions, each ExB probe sweep was analyzed by finding a rectangular area under each ion group according to the half-width-half-maximum (HWHM) and peak of the ion current, similar to a method followed by Beal[11] [2004]. The ion current fractions for operating conditions A, B, and C are shown in Figure 10. At the nominal 200 W power level, the fractions of singly, doubly, and triply charged ions were 90%, 8%, and 2%, respectively. The plot shows two important trends. The first trend is that a higher percentage of multiply charged ions were seen at off centerline angles. A similar trend has been observed by other researchers including Beal[11] [2004] and Ekholm and Hargus[12] [2005] (Busek BHT-200), Kim and Gallimore[13] [1999] (Fakel SPT-100), and Reid et al.[14] [2008] (6 kW laboratory model Hall thruster). The presence of significant fractions of multiply charged ions emphasizes the importance of accurately measuring plume ion distributions at high azimuthal angles due to the possible increase in sputtering and/or contamination of nearby spacecraft components. The second trend is that the percentage of multiply charged ions increased as the thruster power (anode voltage) was increased. A similar trend was recorded by Hofer[15] [2003] when looking along the thruster centerline on a higher power, 5 kW class NASA-173Mv2 laboratory-model Hall thruster. The increase in multiply charged ions with increasing discharge voltage is feasible given the expected increase in plasma electron temperatures with increased discharge voltage and current.

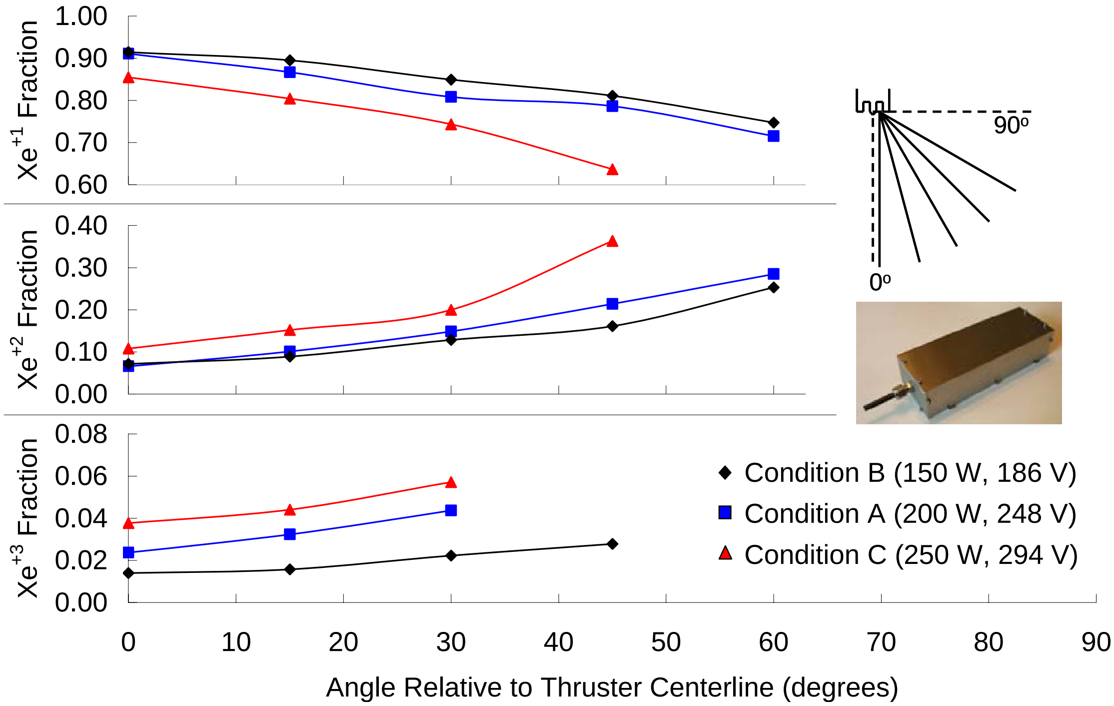

Figure 10. Ion current fractions as a function of azimuthal position for operating conditions A, B, and C. The fractions of multiply charged ions increased with increasing azimuthal angle.

E. Air Force Research Laboratory (AFRL/RZSS)

Testing of low discharge voltage operation of a nominal 6 kW laboratory model Hall thruster was carried out at the AFRL Spacecraft Branch division at Edwards AFB, CA. The laboratory model Hall thruster, shown in Figure 11, was developed at AFRL in collaboration with JPL and the University of Michigan to serve as a standardized test-bed for research of Hall thruster physics. This 6 kW thruster model has similarities to the P5 and NASA173M thruster designs, and has been characterized at AFRL, PEPL, and JPL [Brown[16] 2009; Reid et al.[14] 2008; Jameson et al.[17] 2007]. The magnetic circuit consists of eight outer electromagnets, one inner electromagnet, and an internal trim coil for fine-tuning the magnetic field within the boron nitride (BN) discharge channel. A large channel diameter enabled the placement of a centrally mounted, high-current LaB6 hollow cathode designed by JPL. Auxiliary flow line 1 injected xenon flow through the thruster backplate and around the cathode keeper. This additional flow is utilized to inject a fraction of the cathode neutral flow into the near-cathode region. The schematic in Figure 11 illustrates the internal cathode configuration and auxiliary propellant flow injection.

The 6 kW Hall thruster was operated at low power with xenon gas at a discharge voltage of 150 V and a discharge current of 9.25 A. Charge state measurements were taken with the ExB probe over a range of 1.0 to 1.3 m downstream of the thruster and angles of 0 to 20 degrees relative to the thruster centerline. The ExB measurements were analyzed using a method described by Shastry et al.[18] [2008] of fitting a triangle to each ion group using the peak current and half-width-half-maximum (HWHM), and correcting for effects of CEX reactions in the plume of the Hall thruster. The results, shown in Figure 12, indicate an increase in the percentages of multiply charged ions as the angle was increased from 0 to 20 degrees off axis. This result is in agreement with the charge state data recorded on the 200 W Hall thruster at AFIT as well as the other researchers findings mentioned in the charge state discussions above.

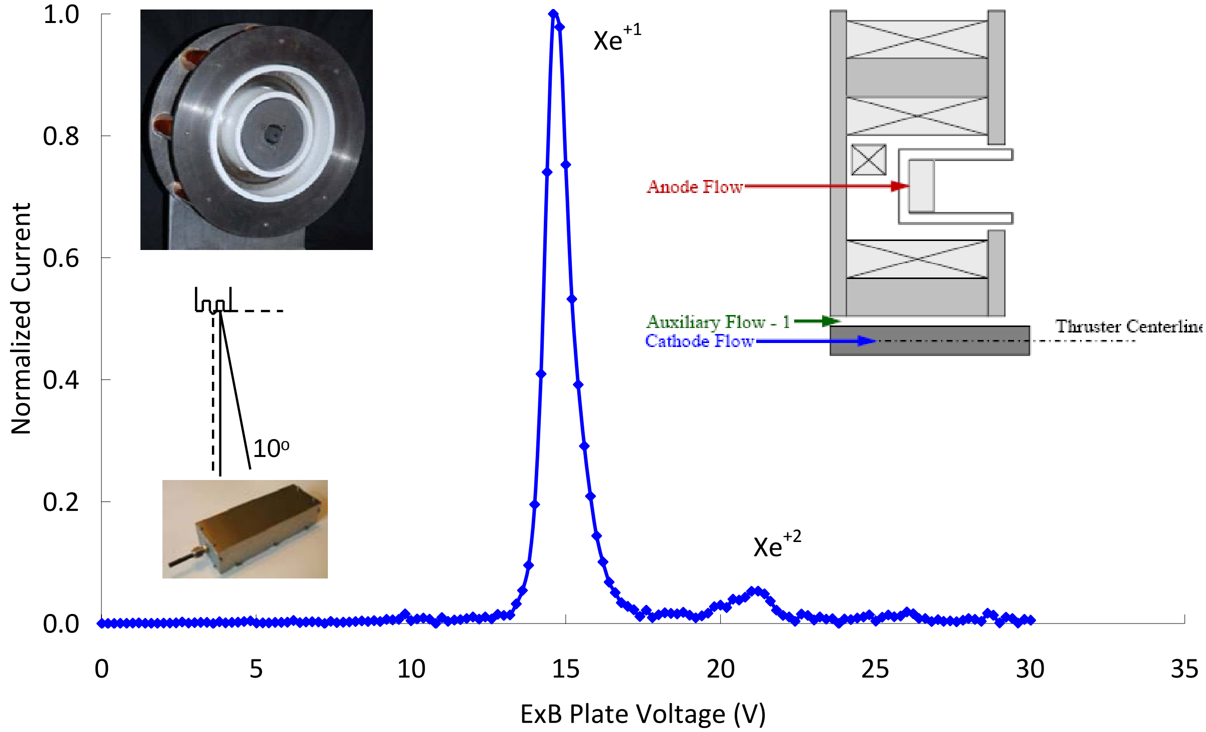

Figure 11. Photograph and schematic of the 6 kW laboratory Hall thruster with a centrally mounted LaB6 hollow cathode. The ExB trace shows relative amounts of singly and doubly charged xenon at a 10 degree zenith angle, 120 cm from the thruster.

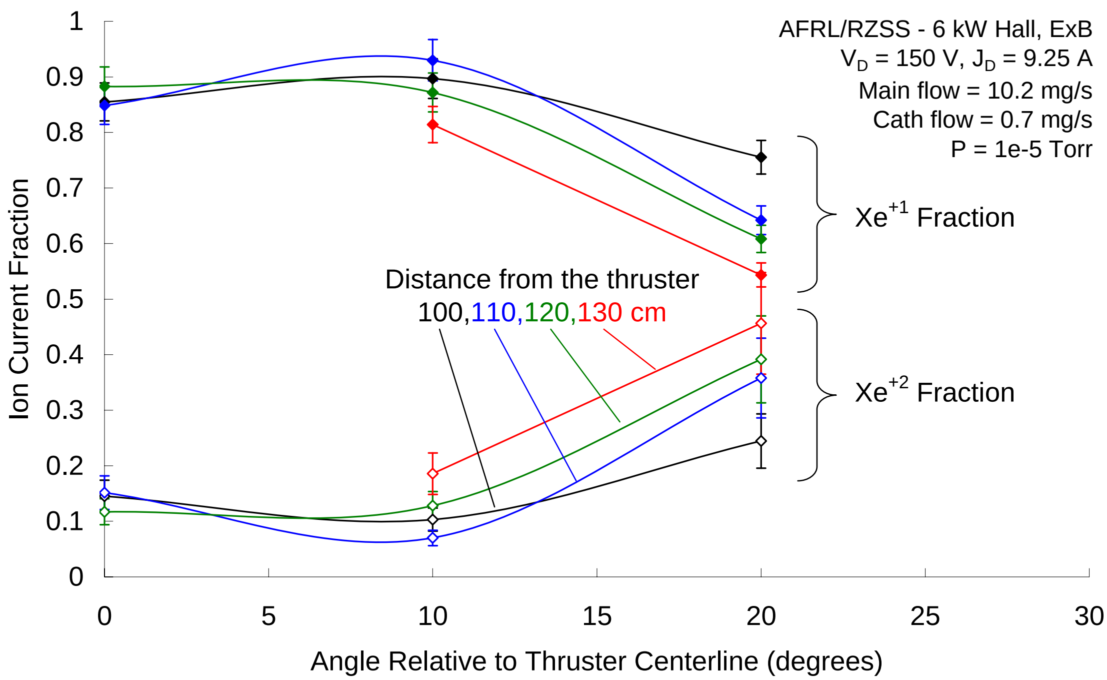

Figure 12. Charge state measurements of the 6 kW laboratory Hall thruster showing an increase in the fraction of multiply charged ions with increasing angles from the thruster centerline.

IV. Conclusion

Remotely located ESA and ExB diagnostic measurements were operated that yielded energy and charge state information on ion sources and Hall thrusters from three test facilities. At CSU, testing of two ion sources demonstrated the performance of ESA and ExB probes to characterize energy and charge state. The ESA showed good agreement between measured energy distribution peaks and the indicated beam voltages of both ion sources. ExB data demonstrated the ability to differentiate ions with respect to mass (Ar/Xe/Bi ions) as well as charge state.

At AFIT, ESA measurements of a 200 W Hall thruster showed variations in ion energy distributions with azimuthal probe position. As the ESA was moved further off the centerline axis, the average energy of the distributions decreased along with the magnitude of the ion current. Data taken at angles of 80 degrees from centerline showed the presence of low energy (60 eV peak) ions with a tail extending to 200 eV. Charge state measurements showed an increase in the fractions of multiply charged ions, both doubly charged and triply charged, with increasing azimuthal position.

Finally, ExB charge state data were described from testing of a 6 kW laboratory Hall thruster at AFRL/RZSS. The low power Hall thruster study at AFRL showed similarities to the 200 W thruster tests at AFIT in that the percentages of multiply charged ions increased when rotating the probe over azimuthal angles from 0 to 20 degrees.

Acknowledgments

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