AEDC plume measurements using bi-directional ion flux probes

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Abstract: A set of five bi-directional ion flux probes was designed and built by the University of Tennessee Space Institute (UTSI) for thruster plume measurements in the AEDC 12V test facility. This paper describes the use of these probes for plume measurements of a 20 kW Busek Hall thruster operated over a wide range of powers. Four probes were placed along the chamber axis, and one was positioned off-axis near one of the chamber baffles. For the probe signals to be measurable at longer distances without a significant increase of the shunt resistance, the collecting area of the probes increases with the distance from the thruster. In this paper, the principle of operation of the bi-directional probes used in the AEDC 12V experiments is analyzed. Appropriate probe models and procedures are presented that allow one to measure the ion currents from the thruster and from the background plasma as well as to determine the density and, possibly, the electron temperature of the background plasma. The axially placed probes were also used to obtain the decay of the ion current density along the axis.

Nomenclature

n_i	=	ion number density
J_i	=	ion current density
e	=	electron charge
I_{sat}	=	ion saturation current
M_i	=	ion mass
A_s	=	sheath area
k, α, β	=	fitting coefficients
R_p	=	probe radius
λ_D	=	is the Debye length

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V_b , V_{bias} = is the probe bias
T_e = electron temperature
J_{CEX} = charge exchange collision current density
I_p = probe current
V_{shunt} = voltage drop across current shunt
R_{shunt} = current shunt resistance
V_p = probe voltage
V_{ps} = power supply voltage
AEDC = Arnold Engineering and Development Center
A_p = probe collector area
V_d = discharge voltage
CEX = charge exchange
ZBL = zero-bias voltage limit

I. Introduction

For typical ground tests of electric thrusters, a common evaluation procedure includes characterization of the plasma plume produced by the thruster.[1] This includes measurements of the ion flux and ion energy distribution at different angles to the thruster axis. For ion flux measurements, a planar probe with a guarding ring[2] (sometimes called as a Faraday probe) and a single gridded retarding probe[3] are usually used. The angular ion flux distribution is measured by moving the probe around the thruster axis. The total ion flux is estimated by integrating over the angular ion flux distribution. These results may be used to deduce the thruster ion performance, including current, energy and propellant (mass) utilization efficiencies, as well as plume angle.[4]

A negatively biased Faraday probe collects the ions, indiscriminately. The collected flux has a broad energy spectrum and consists of the thruster ions and slow ions, which are produced in the plume by ionization of the background gas and due to charge-exchange collisions between ions and background gas atoms.[1] The plasma produced by these processes is referred to as the secondary or background plasma. For Faraday probe measurements, the presence of such plasma results in overestimated values for local and total ion fluxes, and thereby causes an error in the determination of the thruster ion performance. The error can increase with the background pressure and the distance between the probe and the thruster.[5] Busek and MIT have developed an indirect method to determine the "in-orbit" plume with a conventional Faraday probe by introducing background gas into the test facility. Test result showed that the current density increases linearly with background pressure for any given angle. This linear relationship can be used to extrapolate the measurements to zero background pressure, the “in-orbit” condition. A possible way to reduce the contribution of slow ions to the measured ion flux is to use a retarding probe with an ion collector placed behind the grid.[3] The grid is biased slightly negative with respect to the ground so the only ions reaching the collector are those which have enough energy to overcome the retarding potential hill. Because the background plasma supplies mainly low energy ions, it should be possible to repel these ions. The key drawback of this technique is that the retarding potential will also repel slow ions originated in the thruster.

As an alternative to single Faraday and retarding probes, the bi-directional probe should provide more accurate *in-situ* determination of the *true* ion flux from the thruster.[6] A simple bi-directional probe consists of two electrically insulated Faraday probes, each pointed in opposite directions along the common axis. Thruster and background ions are collected by the Faraday probe facing the thruster, while the back faced probe collects essentially ions from the secondary plasma. It is likely that the probe can shadow the directed ions from the thruster, but not “resting” collisionless plasma produced from the background gas. By subtracting the back ion flux from the ion flux measured by the direct probe, the true ion flux can be determined.

A set of five bi-directional ion flux probes was designed and built by the University of Tennessee Space Institute (UTSI) for thruster plume measurements in the AEDC 12 V test facility. This paper describes the use of these probes for plume measurements of a 20 kW Busek Hall thruster. The two-day experimental campaign took place on 9/13/06 and 9/14/06.

II. Hall Thruster Test at Arnold Engineering Development Center

Busek Co.’s 20-kW Hall Effect Thruster (BHT-20K) was demonstrated in the 12-ft diameter vacuum facility (12V) at USAF-Arnold Engineering Development Center (AEDC) (Fig. 1).[7] Test participants included Busek, AEDC, the Aerospace Testing Alliance (ATA), NASA MSFC, and the University of Tennessee Space Institute (UTSI).

The laboratory model Hall thruster was built for a SBIR program funded by AFRL. In testing at AEDC, the thruster was operated at steady-state discharge power levels in excess of 20 kW in both high specific impulse (20 A, 500 V) and high thrust (100 A, 200 V) modes. BHT-20K Hall effect thruster is a nominal 20 kW input power thruster. Under development by Air Force sponsorship, the BHT-20K is designed to produce 1.0 N of thrust at 2750 seconds specific impulse and 70% efficiency. See Table 1 for a summary of nominal operating and performance parameters.

The AEDC test of the BHT-20K and a series of associated experiments quantified the plasma propulsion testing capabilities of 12V. At 20 kW and a discharge current of 100 A, the measured background pressure was 8.0 x 10^{-7} torr, indicating a pumping speed greater than 4 million liters per second. Details of the bi-directional ion flux probes used during these tests are the subject of the sections below.

Table 1. Nominal Operating Paremeters and Performance of the BHT-20K Hall Effect Thruster.

Discharge Input Power	20.25 kW
Discharge Voltage	500 V
Discharge Current	40.5 A
Propellant Mass Flowrate	40.0 mg/sec
Thrust	1.08 N
Specific Impulse	2750 sec
Propulsive Efficiency	72 %

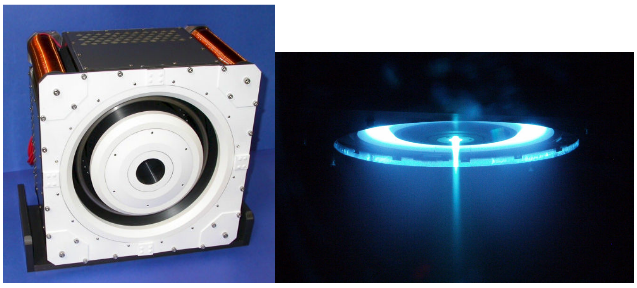

Figure 1. Busek's 20kW Hall Effect Thruster BHT-20K (left) operating at 20-kW in AEDC's 12 V Vacuum Test facility (right). Plume photograph courtesy of AEDC.

III. Probe design, placement and procedure of measurements

The placement of five bi-directional probes in the 12 V chamber is shown in Fig. 2. Table 2 summarizes the dimensions and placements of the probes.

Table 2: Bi-directional ion flux probes for the 12 V AEDC facility.

Probe #	Collector Diam × Length, m × 10^2	Axial Placement, m	Radial placement, m
1	2.54 × 3.28	2.286	≈0
2	4.46 × 3.57	3.286	≈0
3	6.35× 4.35	3.286	1
5	6.35× 4.35	5.286	≈0
6	6.35× 4.35	7.286	≈0

Each bi-directional probe consists of two electrically insulated Faraday probes sharing the same chassis, which can be either floating or grounded (Figs. 3 and 4). Each Faraday probe consists of a planar collector with a guarding ring, which are biased at the same negative potential with respect to ground. The negative bias is in order to collect ions and repel electrons. The planar geometry of the probe collector and the use of a guarding ring around the collector are chosen to minimize measurement uncertainties and errors associated with end and edge effects[8,9] on probe measurements. The gap between the probe collector and the guarding ring is chosen to be less than several Debye lengths for a plasma with the density of 10^{15} m^{-3} and the electron temperature of 1-2 eV. These parameters are expected for the plasma plume at 1 meter away from a typical Hall thruster. It should also be sufficient for less dense plasma in far-plume region of the thruster plume.

The chassis of each Faraday probes is made from aluminum. For Probe #1, nearest to the thruster, the chassis serves also as the guarding ring. The chassis of this particular probe is electrically insulated from the supporting arm because it is connected to the vacuum chamber though a ceramic insert. For the other probes, the chassis is connected to the grounded supporting arm. The bi-directional probes are placed stationary in the chamber (Fig. 2) along the axis and therefore can be subjected to harsh environments, including significant erosion and heating by a high flux of energetic ions from the operating thruster. Because of such unusually harsh environments, a low erosion tungsten-copper alloy was used as the material for the collectors of all *thruster-faced* Faraday probes. This material has also a low yield of ion-induced secondary electron emission. The guarding rings, chassis of the probes, and the collectors of the *back-flux* Faraday probes are made from aluminum. The choice of this material was driven by the desire to minimize the weight of he suspended probes and also by low sputtering requirements (aluminum has a low sputtering yield for Xenon[10]).

The probe current is deduced from measurements of the voltage drop across a shunt, connected electrically between the collector and the power supply.The probe bias is estimated as $V_p = V_{ps} - V_{shunt}$, where V_{ps} is the voltage from the power supply. The shunt resistance must be much smaller than the impedance of the plasma-probe interface but large enough to output a measurable signal. In these experiments, we used shunts of a few 10^2 Ohm for the direct probes and 10^3-10^4 Ohm for the back-flux probe.

Figure 2 shows the placement of the bi-directional probes in the AEDC 12 V chamber. Probes #1, 2, 5, and 6 were at distances 2, 3, 5 and 7 meters (nominal distances) from the thruster, respectively. In addition, an additional (fifth) probe was placed 1 m off the axis, where the simulations predict a

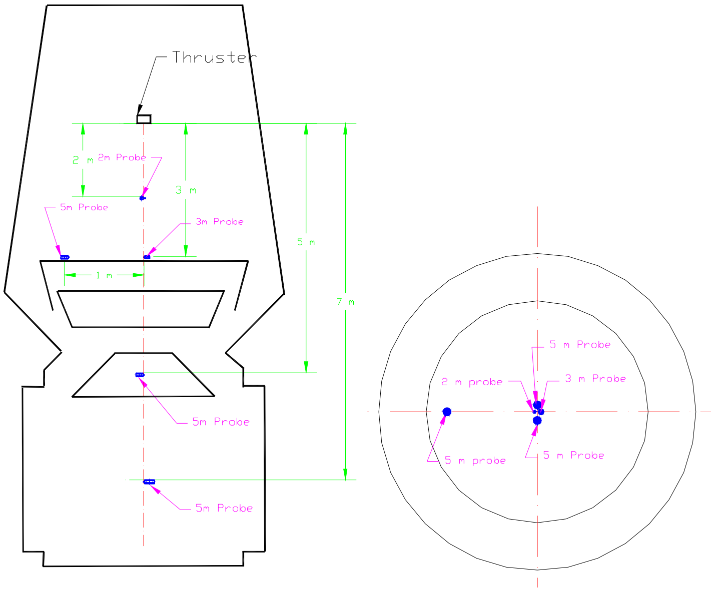

Figure 2. The placement of five bi-directional probes in the AEDC 12 V chamber.

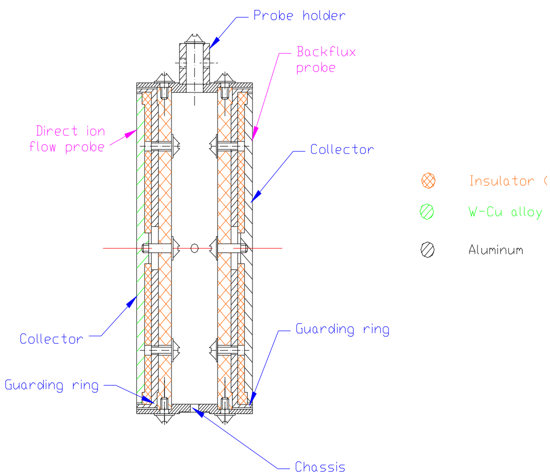

Figure 3. Bi-directional probe design

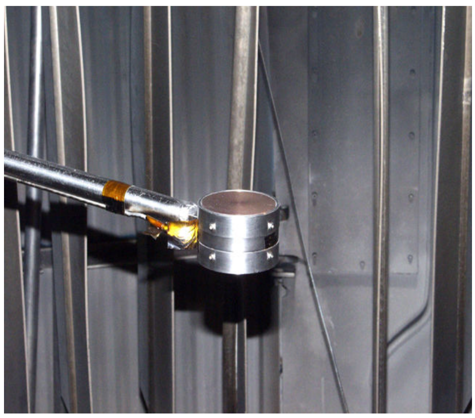

Figure 4. Photograph of a bi-directional probe installed in 12V

stronger contribution of charge exchange ions due to the background gas. This probe was positioned at the same height as probe # 2. Due to the plasma expansion, the ion current density reduces with the distance from the thruster.

For the probe signal to be measurable at longer distances without a significant increase of the shunt resistance, the probe collecting area increases with the distance from the thruster. We considered a plasma expansion from a point source (~ $1/R^2$) in order to select the required area of each probe to collect the comparable values of the ion current at different distances from the thruster.

IV. Operation of the bi-directional probes

In this section, we shall first analyze the principle of operation of the bi-directional probe and explain what these probes can measure. We show that in order to accurately characterize the facility effects on the thruster ion measurements, it is necessary to extrapolate the V-I characteristics of the back ion flux to zero-voltage bias. Then, the density of the background plasma and the electron temperature can be deduced from the appropriate fitting functions, which take into account edge effects and charge-exchange in the sheath-presheath region of the probe.

A. Probe V-I characteristics

In the initial tests, the thruster was operated at low input power regimes and the probe V-I characteristics were measured. For the thruster-faced direct probes, the V-I characteristics exhibit a clear saturation of the probe current when the probe bias is sufficiently negative to repel the plasma electrons (Fig. 5). This is a typical situation for a planar probe with a thin sheath where the current is limited by the source of ions. A comparison of the direct and back flux probe currents (Figs. 5 and 6) measured at the same bias voltage suggests that in each probe case, the former is an order of magnitude larger than the current collected by the back flux probe. Thus, the majority of ions arriving to the direct probe are originated from the thruster and the maximum achievable ion current (saturation value) is limited by the supply of ions from the thruster. In fact, the current saturation value of each probe increases fairly linear with the increase of the flow rate (Fig. 5). Thus, the source-limited regime of the direct ion probe is appropriate for characterization of the thruster ion performance.

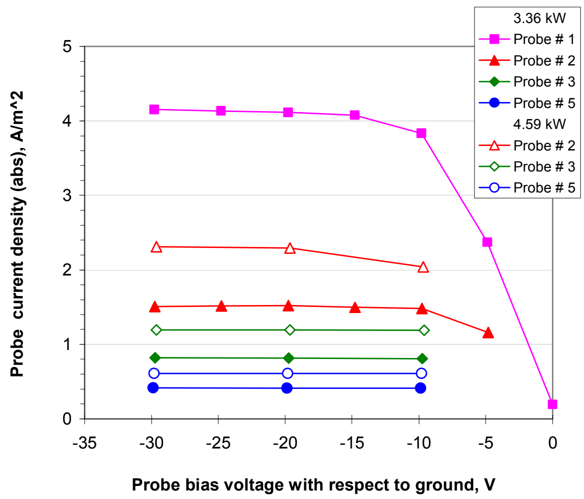

Figure 5. V-I characteristics of the bi-directional probes: THRUSTER-FACED Faraday probes for two xenon operating regimes of the Busek Hall thruster: 3.36 kW (300 V, 100 sccm) and 4.59 kW (300 V, 150 sccm).

The local ion density of energetic ions can be roughly estimated as $n_i = J_i / e\sqrt{2\langle \varepsilon_{ion} \rangle / M_i}$, where e is electron charge, $J_i = I_{sat}/A_p$ is the ion current density estimated for the ion saturation current, I_{sat}, measured by a probe with the ion collecting area, A_p, $<\varepsilon_{ion}>$ is the average energy of ions collected by the direct probe, and M_i is the ion mass. A typical high performance Hall thruster utilizes roughly 80-90% of the applied discharge voltage, V_d,, to accelerate the ions.[11] Assuming $<\varepsilon_{ion}> \approx 0.8eV_d$ for all direct probe locations and the thruster regimes, the estimated density range for energetic ions is 10^{14} m^{-3}- 10^{15} m^{-3}.

B. Relation to background gas effects

In contrast to the direct probes, the V-I characteristics of the back flux probes have no ion current saturation (Fig. 6). This result obviously contradicts to the theoretical V-I of an ideal planar probe with a thin near-wall sheath.[7, 8] As suggested below, combined probe end and sheath edge effects leading to expansion of the effective probe area with the bias voltage[12, 13] could explain this result.

Moreover, because the probes have large dimensions (and so plasma-probe interface) there may be a chance for charge-exchange collisions in the sheath-pre-sheath to produce slow ions, which can be relatively easily captured by the negatively biased probe. The probe guarding rings used in bi-directional probes should reduce probe end effects, but not necessarily sheath edge effects.

For large planar probes in collisionless plasma, experimental and numerical studies demonstrated an ellipsoid-like shape of the sheath edge[12] (geometry effect, density variations along the probe, disturbance of the pre-sheath, etc) leading to an increase of the ion current with the probe bias. By fitting numerical simulations of the planar probe, the ion current density can be deduced as a function of the probe bias[12]:

$$J_i = J_{sat}\frac{A_s}{A_p} \approx \frac{I_{sat}}{A_p}\left(1+\alpha\eta^{\beta}\right), \quad (1)$$

where

$$I_{sat} = 0.6en_s V_{Bohm} A_s = 0.6en_s\left(T_e / M_{ion}\right)^{0.5} A_s \quad (2)$$

is the theoretical ion saturation current for a spherical probe[14] (a plausible analogy for the ellipsoid-like sheath edge), A_s is the sheath area, $\alpha \approx 2.28\left(R_p/\lambda_D\right)^{-0.749}$ and $\beta \approx 0.806\left(R_p/\lambda_D\right)^{-0.0692}$ are fitting coefficients, and $\eta = e\left|V_b\right|/kT_e$. Here, R_p is the probe radius, λ_D is the Debye length, V_b is the probe bias and T_e is the electron temperature. For the probes used in these experiments, R_p/λ_D is roughly 40-50 (estimated using the plasma density derived from the direct ion current measurements (i.e. for energetic ions) and assuming T_e ~ 1-2 eV (also observed in separate Langmuir probe measurements not reported in this paper) to estimate the upper possible bound of the Debye length and thereby, the lower value of the collisionless factor R_p/λ_D). Figure 6 demonstrates that after a certain iteration procedure, we were able to achieve a good agreement between the fitting function (Eq. 2) and the experimental data for back flux probes.

Note that for the lowest probe # 6, the fitting function, Eq. 3, is valid as well, but not for probe # 5. For this upper probe, the sheath expansion alone is apparently not sufficient to explain the measured probe characteristic (Fig. 6b). This behavior is most likely associated with the placement of this probe in the region surrounded by the third baffle in the chamber. Plasma recombination on the baffle might cause an increase of the local neutral gas pressure in this plume region and, possibly, a depletion of the plasma density at the center of the plume as well. A signature of this process may be seen on Fig. 7. It compares the experimental density of the background plasma obtained from fitting of Eq. 1 to the experimental data of Fig. 6 and the density values estimated from the direct probe measurements for energetic ions.

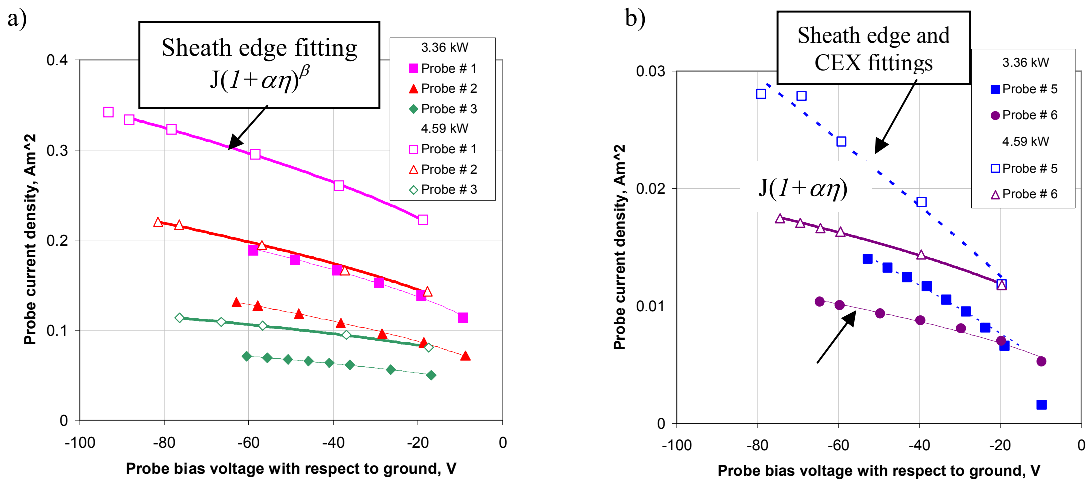

Figure 6. V-I characteristics of the bi-directional probes: BACK-FLUX Faraday probes for two xenon operating regimes of the Busek Hall thruster: 3.36 kW (300 V, 100 sccm) and 4.59 kW (300 V, 150 sccm). The experimental data for probes # 1, 2, 3 and 6 (left figure, (a)) are fitted with the function obtained from numerical simulations and taking into account the sheath edge expansion of a large planar probe. For probe #5 (right figure, (b)), the fitting function is a sum of the sheath expansion and charge-exchange parameters.

A possible increase of the local neutral density due to plasma wall recombination on the baffle may enhance elastic scattering and charge-exchange (CEX) collisions. However, CEX collisions can only keep the probe ion current from its saturation if these collisions occur in the sheath and a plasma volume (presheath) from which the ions are supplied to the probe. Instead of energetic ions, which could escape the probe sheath-presheath region, slow CEX ions have a better probability to be captured by the probe.[14] For Probe # 5, the probability of CEX collisions in the near-probe region, should increase with the neutral density.

In order to account for sheath expansion and CEX collisions in the sheath - presheath region. we modified a fitting function for the probe #5 data. A change of the net charge in the sheath-pre-sheath due to slow ions causes CEX ion current.[15] This current is a function of CEX collisions and the voltage drop in the sheath, i.e. the probe bias voltage. Assuming that the CEX frequency is not a strong function of the probe bias, a fitting function for CEX current density can be

$$J_{CEX} \approx kV_{bias} \quad (3)$$

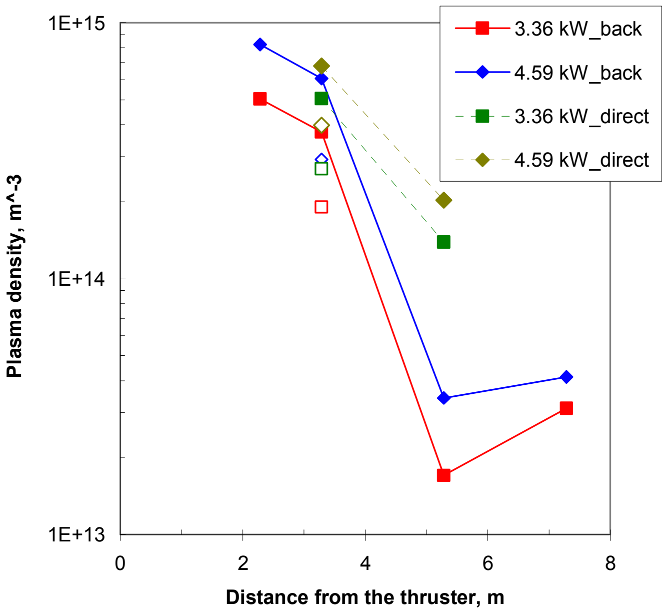

Figure 7. The density of the background plasma (log-scale) obtained from fitting of Eq. 1 to the experimental data of Fig. 6 and the plasma density estimated from measured values of the ion saturation current (Fig. 5) for the thruster-faced probe and Vd = 300 V. Unfilled markers are for the off-axis bi-directional probe (# 3).

where *k* is the fitting parameter. The sum of Eqs. 1 and 3 was used as a fitting function for probe # 5. In reality, a contribution of CEX to the probe current involves more complex phenomena. Besides CEX collisions, other plasma processes might also contribute to the increase of the ion current, including ion flux along the probe,[8] high energy electrons, etc.

C. The ion flux from background plasma

It follows from the probe theory[14] that the sheath of the thruster-faced probe should be at least $(V_b/T_e)^{0.25}$ times thinner than the sheath of the back-flux probe. The reason for this difference is that the thruster ions have energy much larger than the bias voltage and, consequently, larger than the voltage drop across the probe sheath. Thus, the ion density almost does not change in the near-probe sheath. Under such conditions, the probe sheath is similar to so-called matrix sheath.[14] In addition, density variations along the thruster-faced probe are also probably smaller compared to that in the back-flux probe case. As an accumulative result of all of the above, an increase of the effective ion collecting area of the direct probe should be not as strong as for the back-flux probe. Then, the difference between the direct and back ion fluxes measured at the same bias voltage gives an underestimate value of the ion flux from the thruster.

In order to avoid the bias-induced error in the back ion flux measurements, we extrapolate the fitting function Eq. 1 to the zero-bias voltage limit (ZBL) corresponding to the undisturbed (by the sheath expansion) or *true* flux of background ions. This limit occurs when the probe is floating, i.e. the total probe current is equal to zero. By extrapolating Eq. 1 to the ZBL, the *true* ion back flux can be obtained by fitting the experimental data with Eq. 2. The electron temperature is also a fitting parameter. In this analysis, it was between 1-2 eV. Figure 8 shows that the *true* back ion flux at ZBL limit is, however, roughly twice smaller than the back ion flux measured at the probe bias ≈ -30 V.

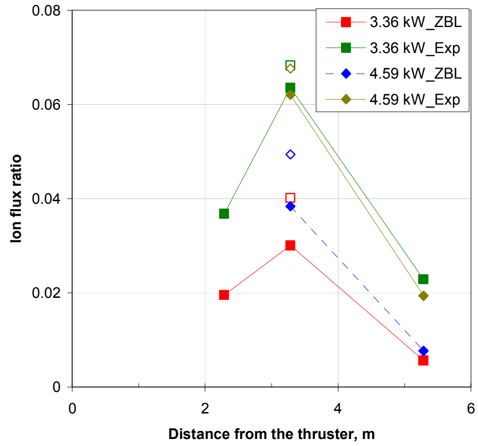

Figure 8. The ratio of the back ion flux to the direct ion flux. The experimental ion back flux and the direct ion flux were measured at the same bias voltage, $V_b \approx$ -30 V, with respect to ground. The back ion flux at the zero bias voltage limit (ZBL) was estimated from Eq. 2, which gives the fitting parameter of Eq. 1. Eq. 1 is fitted to the experimental data of Fig. 4.

V. Ion flux measurements in the AEDC tests

A. Probe performance during the test

In the two-day experimental campaign, the Busek thruster was operated from 3 kW to 20 kW. A set of reliable probe data was obtained in regimes below 10-15 kW. Figure 9 shows results of probe measurements taken on the two different days. Because of a limited number of measurements, it is rather difficult to comment on reproducibility of the probe measurements. We note however, that some irreproducibility seen in Fig. 9 may be also associated with a degradation of probe performance with the thruster power. In fact, for probe # 1, we observed abrupt changes of the direct and back ion fluxes in high power regimes above 10 kW. The current values of these probes become comparable indicating that the probe collectors and their chassis are electrically shorted, i.e. the ion collecting area now combines the probe collectors and chassis. Electrical checks of probe #1 during the test confirmed shorting. Post-run inspections of probe # 1 revealed no electrical shorts. This result may indicate that the electrical shorts during the test might be due to overheating of the probe leading to a reduction of the resistance of, for example, thin film coatings of metals or semiconductor materials. Moreover, almost immediately after start of the AEDC test, the thruster-faced collector of the farthest bi-directional probe (#6) at the bottom of the 12 V was shorted to the chassis most probably because of observed dusting of the probe. In this paper, we focus mostly on the experimental results obtained for the properly operated probes. Figure 9 shows results of the probe measurements in the power range of 3-20 kW at a constant discharge potential of 500 V.

B. Analysis of facility effects

Due to the time constraints of the AEDC test procedure, V-I characteristics of the bi-directional probes were measured only for the low power regimes shown in Figs. 5 and 6. At higher power, the direct probe current was measured with a constant bias voltage of about -30 V, while the back ion flux was measured for two bias voltages of about -30 and -60 V. These two bias voltages of the back probe are obviously insufficient for an accurate determination of the plasma parameters using the fitting functions (Eqs. 2-4). Therefore, for the sake of this analysis, we present mostly unfitted experimental data.

It is clearly seen from Fig.9 that the direct ion flux follows closely the variations of the thruster input power. For all thruster-faced probes, an increase of the discharge voltage and/or the mass flow rate (Fig. 9 right column) causes an increase of the ion current. It appears that the back flux probes sensed a more complex response of the background plasma to the same variations of the thruster regimes (Fig. 9). In particular, for the probes placed above the first baffle and along the axis (# 1 at 2 m, and #2 at 3 m), the background flux does not change much with the power, while the ratio of the background ion flux to the direct ion flux reduces from ~ 20% to 2% (Fig. 10). For probes # 3 and 5, the increase of both direct and back ion fluxes occur nearly linearly with the power, so the back

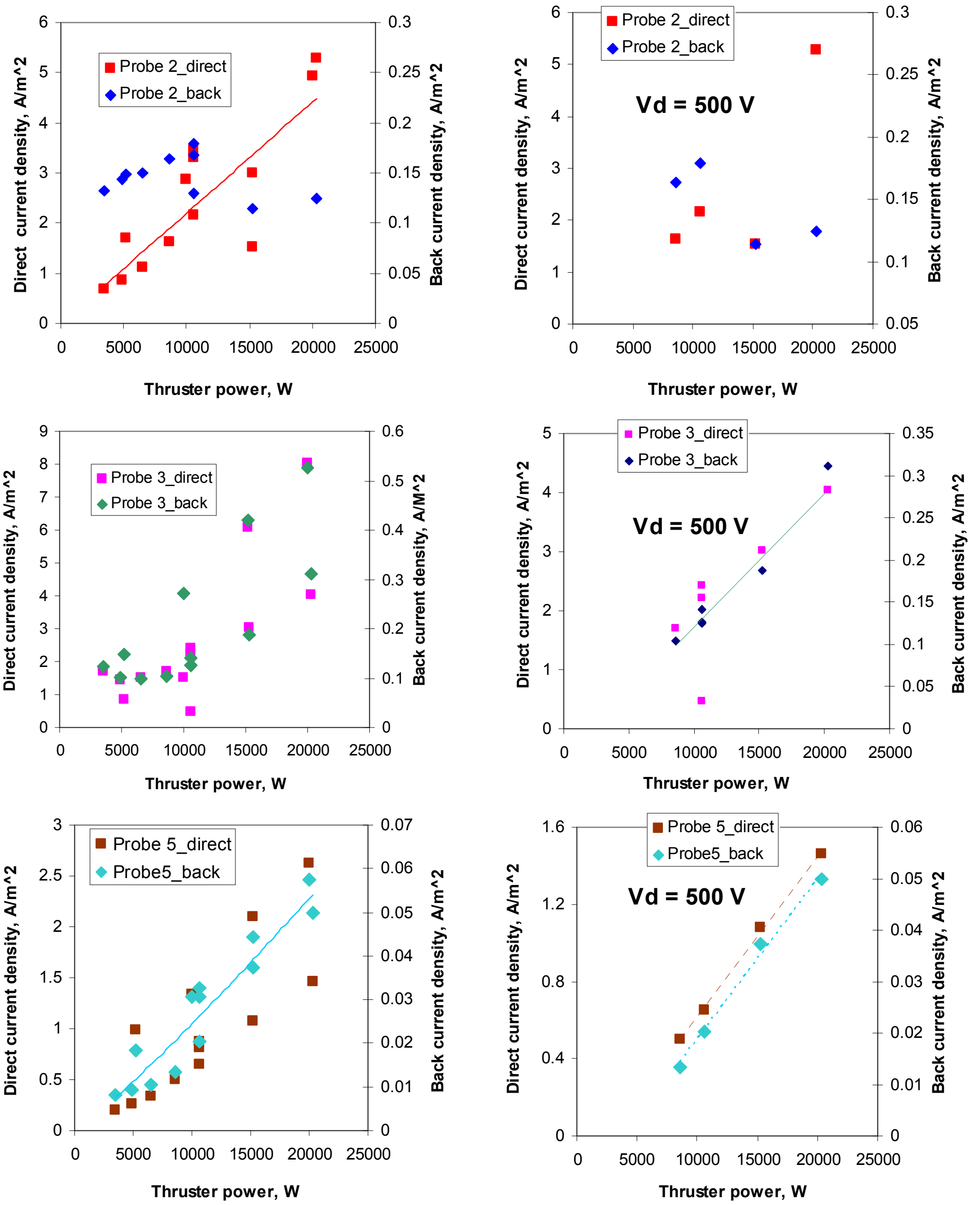

Figure 9. Results of ion flux measurements using bi-directional probes for different values of the thruster input power. The data on the right column is for a constant discharge voltage of 500 V. The measurements were taken for the same probe bias of about -30 V with respect to ground for both direct and back-flux collectors of the bi-directional probes.

ion flux fraction remains almost the same (< 10% variation). Both probes # 3 and 5 are placed near the first and second, and third baffles, respectively, so a wall recombination of the plasma jet from the thruster takes place there acting as a supply of the background gas to the volume. In future AEDC facility tests, it is important to validate and explain these critical observations with more detailed measurements and numerical simulations. It is particularly important to understand and to be able to predict recycling (by ionization) of the wall recombined neutral gas atoms (CEX and impact ionization) in the plasma plume. Figure 11 shows that the background plasma density can be comparable and may exceed the plasma density in of the thruster plume.

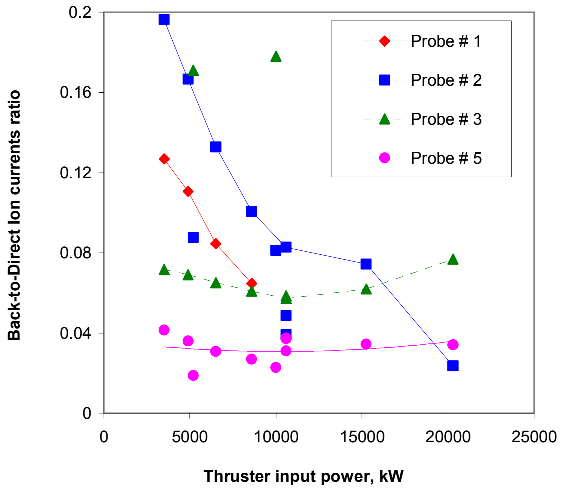

Figure 10. The ratio of the back ion current to the direct ion current obtained from measurements of the thruster faced and back flux collectors of the bi-directional probes biased at the same voltage of about-30 V with respect to ground.

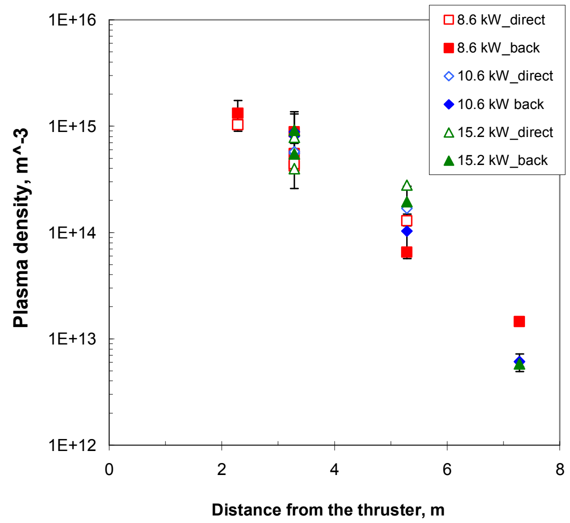

Figure 11. Plasma density of the background plasma and the plasma jet (log-scale). The background plasma density was deduced from back-flux measurements using Eq. 3. Error bars are between the measured and extrapolated (ZBL) values of the density. The ZBL density was obtained very roughly using the fitting function of Eq. 2. The density in the plasma jet was deduced from the direct probe measurements using Eq. 1

VI. Summary, recommendations and future work

We developed and demonstrated the bi-directional ion flux probes for plasma plume measurements of Hall thrusters. The bi-directional probes can be used to simultaneously monitor the status of both background plasmas and the plasma jet. The probe allows one to measure the ion currents from the thruster and from the background plasma, as well as to determine the density and, possibly, the electron temperature of the background plasma. For that purpose, a simplified probe model and procedure were developed and analyzed.

The ability of the bi-directional probe to monitor background plasma and plasma jet from the thruster is particularly important for tests of high power thrusters, when the thruster operation approaches the capacity limit of the cryogenic pumping system. According to the probe measurements, the AEDC 12V facility was able to handle the high power (> 10 kW) operation of the Busek thruster without increasing the presence of the background plasma in the upper part of the 12 V chamber. However, the wall recombination of the plasma jet on the baffles probably leads to a local increase of the background plasma effect, including at the centerline of the vacuum vessel below the third baffle and near the first and second baffles. In particular, the ratio of the background ion flux to the total ion flux increases at these locations. This behavior suggests that at high power levels the far-plume measurements in the 12 V chamber may be limited by a distance of 3 meters from the thruster.

Acknowledgments

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References

[1] Pollard, J. E., Diamant, K. D., Khaims, V., Wethman, L., King, D. Q., and de Grys, K. H., AIAA paper 2001-3351, Slat-Lake City UT, July 2001.

[2] Wagner, H., Weiseman, K., and Angew. Zs., *Phys*. **16**, 230 (1963).

[3] Diamant, K. D., Pollard, J. E., Cohen, R. B., Raitses, Y, and Fisch, N. J., *Propul. Power*, **22**, 1396 (2006).

[4] Richard, R. H., Jankovsky, R. S., and Gallimore, A. D., *Propul. Power* **22**, 721 (2006).

[5] Azziz, Y., Martinez-Sanchez, M., and Szabo, J., AIAA-2006-4484, Sacramento, CA, July, 2006

[6] Raitses, Y., Staack, D., Dunaevsky, A., Dorf, L. and Fisch, N. J., IEPC paper 03-0139, the 28th International Electric Propulsion Conference, Toulouse, France, March 2003.

[7] Polzin, K., Dawbarn, A., Tatum, K., Crider, D., Brown, M., Moeller, T., Raitses, Y., Szabo, J., Byrne, L., and Boyd, I., "Demonstration of High Power Plasma Propulsion Test Capabilities at Arnold Engineering Development Center," 54th Joint Army-Navy-NASA-Air Force (JANNAF) Propulsion Meeting (JPM) / 5th Modeling & Simulation Subcommittee (MSS) / 3rd Liquid Propulsion Subcommittee (LPS) / 2nd Spacecraft Propulsion Subcommittee (SPS) Joint Meeting, Denver, CO, May 14-17, 2007.

[8] Lochte-Holtgreven, W., *Plasma Diagnostics*, (North-Holland Publishing House, Amsterdam) 1968.

[9] Chen, F. F., *Mini-course on Plasma Diagnostics*, IEEE-ICOPS meeting, Jeju, Korea, June 2003.

[10] Rosenberg, D. and Wehner, G. K., *J. Appl. Phys*. **33**, 1842 (1962)

[11] Hofer, R. R. and A. D. Gallimore, A. D., Propul. Power 22, 732 (2006)

[12] Wehner, G. K., Phys. Rev. **102**, 690 (1956); T. E. Shredian, *Phys. Plasmas* **7**, 3084 (2006)

[13] Laframboise, J. G., University of Toronto, Institute for Aerospace Studies, Report No. 100, 1966.

[14] Lieberman, M. A., and Lichtenberg, A. J., *Principles of Plasma Discharges and Materials Processing* (Wiley, New York) 1994.

[15] Z. Sternovsky, S. Robertson, and M. Lampe, Phys. Plasmas 10, 300 (2003).