EFFECTS OF DESIGN AND OPERATING CONDITIONS ON ACCELERATOR-GRID IMPINGEMENT CURRENT

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Fort Collins, CO 80523

Abstract

A simple method for experimentally measuring the neutralization length, which is defined as the length of the region downstream of the accel grid within which all ions produced with low kinetic energies impinge on the grid, is presented. Preliminary calculations and supporting data are presented to show that charge-exchange, not single- or multi-step electron-impact ionization collisions are the dominate production mechanism for low-energy ions. Effects of varying the thruster operating conditions, grid set geometry and neutralizer operating conditions on the neutralization length are included and they show that the changes predicted using a simple theory agree quite well with measured values. A 1-D model which describes the production of charge-exchange ions and yields results that agree with measured impingement currents to within ±30% is presented. The use of this 1-D model also suggest that the higher-than-expected impingement-current-to-beam-current ratios observed in many ground-based tests are due to facility effects and will not be present when ion thrusters are operated in high-pumping speed facilities or space.

Introduction

The primary objective of ion optics, i.e. the screen and accelerator (accel) grids of an electrostatic ion thruster, is to accelerate ions produced within a discharge chamber to high-exhaust velocities. In properly designed ion optics, these high velocity beamlet ions exit the thruster and produce thrust without striking the grids themselves. However, if the optics are poorly designed it is possible that a significant number of beamlet ions will strike the accel grid causing it to sputter erode. In addition to striking the accel grid directly, some beamlet ions will have charge-exchange collisions with neutral atoms (e.g. unionized propellant atoms or background atoms in the vacuum tank) and produce ions with low kinetic energies that may be drawn into the accel grid and also contribute to its erosion. Low-energy ions could also be produced downstream of the accel grid as a result of collisions between electrons and neutral atoms. The relative magnitude of this low-energy ion current component compared to that created by charge-exchange collisions is determined by the density and energy-distribution of the electrons in the beam plasma.

Kerslake developed an analytical model to predict the low-energy-ion-impingement current under prescribed ion-thruster operating conditions. Similarly, Peng, et al. developed a three-dimensional numerical simulation which

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which could introduce significant errors in the \( \mu \)A-level currents measured during some experiments. The clamping diodes shown on the figure were used for the majority of the experiments conducted to guarantee that the neutralizer emission current \([I_B]\) exactly matched the beam current \([I_B]\) independent of the polarity of the coupling voltage \([V_C]\). During this study four different grid sets were used: two constructed from molybdenum and two from a poly-crystalline, synthetic graphite. The dimensions of these grid sets are summarized on Table 1. The 19-hole and both 7-hole grid sets were mounted at the center of the masked-down SERT II thruster where uniform discharge plasma properties could be assured.

To measure the properties of the downstream region, two probes were used. Specifically, a bent-emissive probe described previously\(^4\) was used to measure the potential fields downstream of the grid sets and a 3.2-mm-dia. spherical Langmuir probe was used to measure plasma properties (electron temperature and density). Both of these probes could be moved axially and radially throughout the downstream region to collect potential and plasma-density information. All tests were conducted in a diffusion-pumped, 1.2-m-dia.-by-5.4-m-long, stainless-steel vacuum chamber, and unless noted otherwise all tests were conducted using xenon as the propellant.

### Relative Magnitudes of Impingement-Ion-Production Mechanisms

In a previous investigation, a 1-D theory to predict the differential impingement current per ion beamlet \([dJ]\) created within a differential length \([dz]\) was presented.\(^4\) This differential current, which was calculated by determining the number of low-energy ions created by charge-exchange and electron-impact ionization collisions is given by

\[
dJ_i = \int_0^\infty \sigma_{ce}(z) n_e(z) \, dz + e n_e(z) n_i(z) \sigma_e(\nu_e, \Lambda_e) \, dz \quad , (1)
\]

where the product of \(J_B\) (the beamlet ion current), \(\sigma_{ce}\) (the charge-exchange cross-section), \(n_i(z)\) (the neutral-density profile) is a production rate per unit length of charge-exchange ions. Multiplying this rate by the differential length \([dz]\) yields the differential current due to charge-exchange collisions. Similarly, the differential current due to electron-impact ionization is given by the product of \(n_e(z)\) (the electron density), \(\sigma_e(\nu_e)\) (the electron-impact-ionization cross-section), \(\nu_e(z)\) (the electron velocity), \(n_i\) (the neutral-density profile), and \(\Lambda_e\) (the cross-sectional area associated with impact ionization within one beamlet).

Only the neutral-density profile is not known in the charge-exchange component of Eq. 1. On the other hand, the majority of the terms in the electron-impact component are difficult to determine so it is advantageous to determine if this component can be neglected in comparison to the charge-exchange component. The magnitude of the charge-exchange component can be estimated as the product of the production rate of charge-exchange ions and the length \([z]\) of a cylindrical volume containing neutral-ground-state atoms with a density \([n_i]\) through which a beam of ions is flowing. From the survival equation the ratio, of the charge-exchange ion current to the beamlet-ion current is given by

\[
1 - \exp[-\sigma_{ce} n_i z].
\]

Using typical numbers for the cross-section (i.e. \(50 \times 10^{-16} \text{ cm}^2\)), the neutral density \((1 \times 10^{12} \text{ cm}^{-3})\) and an estimated length of the region \((z = 1 \text{ cm})\) a ratio of 0.5\% is obtained. For comparison, the ratio of the impingement current produced by electron-impact ionization to the beam current was also computed using the simple model of 1-D of neutral-ground-state atoms flowing from the grids through beam-plasma electrons at a density \(n_e = 10^9 \text{ cm}^{-3}\) and a temperature of 11,000 K (1 eV). This ratio is given by

\[
4 \left[ \frac{1 - n_i}{n_i} \right] \left[ \frac{T_n m_e}{T_{ne}} \right] \left[ 1 - \exp[-\sigma_{ce} n_i z] \right] . (2)
\]

where \(T_n\) is the neutral-atom temperature (\(\approx 500 \text{ K}\)), \(m_a\) and \(m_e\) are the neutral atom and electron mass and \(n_i\) is the propellant-utilization efficiency. Using a maximum impact-ionization cross-section \((\sigma_{ei} = 10^{16} \text{ cm}^2)\), a conservative propellant utilization efficiency of 0.5, and a length \(z = 1 \text{ cm}\) a value of 0.5\% is obtained. Hence even with these extreme assumptions, the electron-impact-ionization contribution to the impingement current should be substantially less than that due to charge-exchange (0.1\% v 0.5\%). It is also possible that metastable atoms produced in the ion source could flow through the electrons of the beam plasma and be ionized. Because the density of these atoms

<table>
<thead>
<tr>
<th>Grid Designation</th>
<th>19-hole</th>
<th>7-hole, 1 cm</th>
<th>7-hole, (1/2) cm</th>
<th>15 cm SHAG</th>
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<tr>
<td>Beam Dia. (cm)</td>
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<td>2.2</td>
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<tr>
<td>Grid Material</td>
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</table>
should be at least an order of magnitude below the ground-state-neutral density and the peak cross-sections for ionization of ground state and metastable neutral are similar, it is argued that impingement-ion production from metastables should be negligible ($< 0.1\%$). The preceding preliminary calculations suggest that charge-exchange collisions dominate the production of low-energy ions, that single-step ionization may produce a few ions, and that ionization from the metastable state is very unlikely.

Because the order-of-magnitude calculations did not show conclusively the electron-impact ionization was negligible, a preliminary experiment was conducted in which one species of gas was used as the propellant and a second species was introduced into the vacuum tank either locally (near the accel grid) or remotely (2.7 m downstream of the accel grid). The increases in the background atom density were measured using a hot-filament-pressure gauge located 1 m downstream from the thruster. Different gaseous species were used for the propellant and backfill because the cross-sections for charge-exchange between ions of one species and atoms of another is 3 orders of magnitude smaller than the cross-sections for charge-exchange between ions and atoms of the same species. While the cross-sections for charge-exchange between ions and atoms of two species is very small, the electron-impact-ionization cross-sections are only 2 to 3 times larger for xenon (one species) than argon (the other species). Thus, any changes in the impingement current induced by increasing the background density of the second species should be due to electron-impact ionization of the background atoms and not charge-exchange. This experiment to determine the magnitude of the electron-impact ionization was conducted using the SERT II ion thruster with the 19-hole grid set operated at the conditions presented in the legend of Fig. 2. The impingement current was measured as the background atom density was increased by locally (the open symbols) and then by remotely (the solid symbols) introducing the backfill gas. In addition to the effects of background density on impingement current, this figure also shows the effects of changes in propellant utilization ($n_e$) (accomplished by holding the beam current constant and varying the thruster flow rate) on impingement current. These data show that remote introduction of argon when the thruster is operated on xenon propellant (Fig. 2a) causes negligible changes in the impingement current and that local introduction of argon causes the impingement current to increase ~5%. It is argued that this small increase in the impingement current is due to modest argon ingestion, its subsequent ionization within the discharge chamber, and extraction as a small fraction of the beam current that does charge-exchange with the argon backfill. The data of Fig. 2a show that changes in the propellant utilization cause the greatest changes in the impingement current and considering only three sources for neutral atoms (the discharge chamber, the local backfill, and the remote backfill) these data suggest charge-exchange between the xenon beam ions and xenon propellant atoms from the discharge chamber (determined by the propellant utilization) dominate the production of low-energy ions.

The impingement current v. background-atom-density data obtained using argon as the propellant and xenon as the backfill gas are presented on Fig. 2b and they show great impingement-current sensitivity to local xenon backfill (open symbols). Currently two reasons for this trend have been postulated. First, when xenon is introduced locally, the thruster ingests some of it and since the discharge voltage is high for a thruster operating on argon, this ingested xenon is ionized readily and becomes a substantial contributor to the extracted beam current. The xenon beam ions can then charge-exchange with the back-filled xenon atoms and thus contribute to the impingement current. This mechanism is supported by the observation of a steady decrease in the discharge voltage to a value similar to that for a thruster operating on xenon as the background-xenon density increases. Second, it may be argued that a greater number of thermalized (Maxwellian) electrons possess enough energy to ionize the xenon because its ionization potential is lower than that of argon (the other species). Thus, any changes in the impingement current induced by increasing the background density of the second species should be due to electron-impact ionization of the background atoms and not charge-exchange. This experiment to determine the magnitude of the electron-impact ionization was conducted using the SERT II ion thruster with the 19-hole grid set operated at the conditions presented in the legend of Fig. 2. The impingement current was measured as the background atom density was increased by locally (the open symbols) and then by remotely (the solid symbols) introducing the backfill gas. In addition to the effects of background density on impingement current, this figure also shows the effects of changes in propellant utilization ($n_e$) (accomplished by holding the beam current constant and varying the thruster flow rate) on impingement current. These data show that remote introduction of argon when the thruster is operated on xenon propellant (Fig. 2a) causes negligible changes in the impingement current and that local introduction of argon causes the impingement current to increase ~5%. It is argued that this small increase in the impingement current is due to modest argon ingestion, its subsequent ionization within the discharge chamber, and extraction as a small fraction of the beam current that does charge-exchange with the argon backfill. The data of Fig. 2a show that changes in the propellant utilization cause the greatest changes in the impingement current and considering only three sources for neutral atoms (the discharge chamber, the local backfill, and the remote backfill) these data suggest charge-exchange between the xenon beam ions and xenon propellant atoms from the discharge chamber (determined by the propellant utilization) dominate the production of low-energy ions.

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S. the typical one measured downstream of the 7-hole, 1-cm dia. grid set and shown in Fig. 4 are used determine if an ion will strike the grid. From this figure it is evident that the potentials downstream of the accel grid show two distinct regions, one containing strong electric fields (the near-field region) the second having weak electric fields (the far-field region). The distance between the boundary between the regions and the accel grid is defined as the neutralization length \( l_\text{a} \) because electrons from the far-field region that reach this boundary should be reflected downstream, hence no electrons should be present upstream of \( l_\text{a} \). The data of Fig. 4 also indicate that all charge-exchange ions produced in the near-field region \( 0 < z < l_\text{a} \) will impinge on the accel grid and contribute to the impingement current. A careful examination of the figure reveals that only very slight potential barriers exist near the centerline of individual ion beamlets. At first glance it may seem that they might prevent charge-exchange ions created in the far-field region from migrating upstream of \( l_\text{a} \) and reaching the accel grid. Closer examination shows, however, that these barriers do not represent a continuous potential ridge across the entire ion beam; thus, it is possible for charge-exchange ions produced in the far-field region to contribute to the impingement current by flowing between the ion beamlets. The data of Fig. 4 also show that no substantial, axial-potential gradients exist in the far-field region so the rate at which charge-exchange ions produced in this region impinge on the accel grid is determined by the direction they are moving when created. If it is assumed these ions are created with an isotropic velocity distribution, the probability that an ion created downstream of \( l_\text{a} \) will impinge on the accel grid is equal to the ratio of the solid angle subtended by the accel grid (determined at the point where the ion was created) to the total solid angle through which ions can escape \( (4\pi) \). Assuming further that the creation of charge-exchange ions is independent of radial position (a 1-D approximation) this ratio of solid angles (or accel-grid-view factor \( F_\text{g} \)) is given by

\[
F_\text{g} = \frac{1}{2} \left[ 1 - \frac{z}{\left( \frac{l_\text{a}}{l_\text{a}} + z \right)^2} \right],
\]

\( l_\text{a} \) being the neutralization length. The effects of neutralizer bias voltage on the Maxwellian electron temperature and impingement current are illustrated in Fig. 3. Effects of the neutralizer bias voltage on the Maxwellian electron temperature and impingement current indicate that the temperature that is about 0.5 eV and negative bias voltages induce a temperature that is about 3.5 eV. This change in temperature should induce a 10-order-of-magnitude increase in the electron-impact ionization rate factor (the relative-velocity/cross-section product). It is assumed that the other downstream plasma properties remain constant (i.e. the neutral and electron densities), such a large increase in rate factor should induce a gigantic increase in impingement current. The data of Fig. 3b show, however, that impingement current remained almost constant at 1.6 mA (1% of \( J_\text{a} \)) as the neutralizer-bias voltage was changed from 50 to -50 V. Thus it is concluded that electron-impact ionization by Maxwellian beam-plasma electrons does not contribute significantly to the production of low-energy ions that can be subsequently drawn into the accel grid and contribute to the impingement current.

Theoretical Development

Determination of the Differential-Impingement-Current-Integral Limits

On the basis of the analysis and experimental results of the preceding section it is argued that the charge-exchange reaction is the only significant production mechanism for low-energy (impingement) ions and consequently only the first differential component of Eq. 1 need be integrated. Since the final destination of a charge-exchange ion is controlled by the potential field where it is created, potential maps like the one shown in Fig. 4 are used determine if an ion will strike the grid. From this figure it is evident that the potentials downstream of the accel grid show two distinct regions, one containing strong electric fields (the near-field region) the second having weak electric fields (the far-field region). The distance between the boundary between the regions and the accel grid is defined as the neutralization length \( l_\text{a} \) because electrons from the far-field region that reach this boundary should be reflected downstream, hence no electrons should be present upstream of \( l_\text{a} \). The data of Fig. 4 also indicate that all charge-exchange ions produced in the near-field region \( 0 < z < l_\text{a} \) will impinge on the accel grid and contribute to the impingement current. A careful examination of the figure reveals that only very slight potential barriers exist near the centerline of individual ion beamlets. At first glance it may seem that they might prevent charge-exchange ions created in the far-field region from migrating upstream of \( l_\text{a} \) and reaching the accel grid. Closer examination shows, however, that these barriers do not represent a continuous potential ridge across the entire ion beam; thus, it is possible for charge-exchange ions produced in the far-field region to contribute to the impingement current by flowing between the ion beamlets. The data of Fig. 4 also show that no substantial, axial-potential gradients exist in the far-field region so the rate at which charge-exchange ions produced in this region impinge on the accel grid is determined by the direction they are moving when created. If it is assumed these ions are created with an isotropic velocity distribution, the probability that an ion created downstream of \( l_\text{a} \) will impinge on the accel grid is equal to the ratio of the solid angle subtended by the accel grid (determined at the point where the ion was created) to the total solid angle through which ions can escape \( (4\pi) \). Assuming further that the creation of charge-exchange ions is independent of radial position (a 1-D approximation) this ratio of solid angles (or accel-grid-view factor \( F_\text{g} \)) is given by

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where \( r_a \) the exposed accel grid radius, is not necessarily equal to the active radius of the accel grid through which the ion beam is extracted. It is noted that Ruyten\textsuperscript{8} is developing a view-factor model which reflects 2-D effects and can, therefore, be used to model this aspect of charge-exchange-impingement-current production.

Because charge-exchange ions can originate from two distinct regions, the impingement current must be calculated as the sum of two integrals. First, the charge-exchange-ion rate-factor must be integrated from 0 to \( t_n \) to account for all charge-exchange ions created in the near-field region and second the product of the accel-grid-view factor and the rate-factor must be integrated from \( t_n \) to \( \infty \) to account for all the ions produced downstream of \( t_n \). Specifically, the impingement current is calculated by evaluating the following integrals:

\[
\hat{j}_t = \hat{j}_B \int_0^{t_n} n_o(z) \, dz + \hat{j}_B \int_{t_n}^{\infty} F_g n_o(z) \, dz
\]

Assuming the neutral density profile is constant within the region from \( t_n \) to \( \infty \), the integral of the accel-grid-view factor can be evaluated yielding an effective length for the impingement of charge-exchange ions created downstream of \( t_n \). This length (the effective charge-exchange-ion-extraction length \( [t_{ce}] \)) is equal to \( 1/4 \) of the exposed accel-grid diameter.

Neutral Density Profile Calculations

The last variable required before Eq. 4 can be integrated is the neutral density profile \( [n_o(z)] \). This profile can be estimated using a Monte-Carlo simulation procedure developed for radiative-heat-transfer calculations.\textsuperscript{9} This simulation procedure can be used because the motion of photons within the appropriate radiative enclosure approximates the motion of isotropic-neutrals in the low-pressure environment of a grid set. The geometry used to model the aperture pairs used in these studies is pictured on Fig 5. It shows the grid and other domain boundaries as either diffuse (absorption and outward re-emission with a cosine distribution), specular (angle-of-incidence equals angle-of-reflection), or black (completely absorbing). For this simulation, the surface located downstream of the accel grid, between adjacent apertures was assumed to be black. This models a single-aperture grid set. For multi-aperture sets, this surface would need to be gray-specular with a grey scale becoming increasingly black for holes near the periphery of the grid set and at axial locations far downstream.

The simulation procedure involves the emission of neutral/photon particles from the planar, discharge-plasma emission surface and tracking them until they reach one of the two black surfaces. Neutral/photon particle emission with equal probability in all downstream directions from the discharge-plasma emission surface is prescribed to simulate the flow of neutrals from the discharge chamber. The neutral-density profile at the downstream surface (located at an axial position \( z \)) is determined by 1) counting the number of particles absorbed on it per unit area (equivalent to the number of neutrals crossing this area per unit time), 2) converting this count profile to a current-density profile (i.e. neutral/cm\(^2\)/sec) through division by the area of the surface and 3) dividing by the mean speed of atoms with the discharge-chamber temperature to obtain a radial, atom-density profile. This simulation procedure was repeated for several \( z \) values to obtain the complete, axi-symmetric downstream density field.

Applying the Monte-Carlo-simulation procedure for the 7-hole, 1-cm grid set, the normalized, propellant-density profile presented on Fig. 6 as the circular points was obtained. These density data were normalized by dividing the number density at position \( z \) by the propellant density within the discharge chamber \( [n]\). To approximate the Monte-Carlo results, the exponential curve fit shown as the solid line on the figure was used. This and similar curve fits describing the neutral density expansions for other grids were quantified using a characteristic length (the source-neutral-expansion length \( [t_{ce}] \)) and the source-neutral exit fraction \( [F_s] \). For the data of Fig. 6, \( t_{ce} \) is 0.48 cm and \( F_s \) is 0.69 (i.e. the density at the accel grid is 69\% of the source density \([n]\)). The values of the source-neutral-expansion lengths and the source-neutral exit fractions for the grid sets of interest, determined in this way, are presented in Table 2.

Using the approximation for the neutral density profile, the impingement current can be calculated by substituting the exponential-curve-fit expression [Fig. 6] into Eq. 4 to obtain the following integrals for the production of
impingement ions via charge-exchange collisions between beamlet ions and propellant atoms

\[ J_{i,s} = j_B \sigma_c e n_s (1 - \eta_b) F_s \int_{0}^{\ell_s} \exp \left[ -\frac{z}{\ell_s} \right] \, dz \]

In this equation the term \( (1 - \eta_b) \) accounts for the reduction in the source-neutral density as the beam current increases. Integrating Eq. 5 results in the following equation for the source-dominated-impingement current \( [J_{i,s}] \)

\[ j_B \sigma_c e n_s (1 - \eta_b) F_s \int_{0}^{\ell_s} \left[ 1 - \frac{z}{\ell_s} \right] \exp \left[ -\frac{z}{\ell_s} \right] \, dz \]

where the last integral must be evaluated numerically.

In addition to charge-exchange ions being created by collisions between beamlet ions and propellant atoms, it is also possible that ions could be created by collisions between beamlet ions and background neutral atoms present within vacuum facilities having finite pumping speeds. To determine this background-dominated-impingement-current component \( [J_{i,b}] \), a constant (background) neutral density \( n_b = n_0 \) was substituted into Eq. 4. Integration then yields

\[ J_{i,b} = \frac{j_B \sigma_c e n_b}{2} \left( \frac{\ell_s^2}{\ell_0^2} + \ell_s \right) \]

The total impingement current, which can be compared to a measured-impingement current is obtained by summing both the source- and background-dominated-impingement currents, i.e.

\[ J_i = J_{i,s} + J_{i,b} \]

The remaining unknown in these equations is \( \ell_n \), so a primary objective of the research described next will be to determine \( \ell_n \) analytically and experimentally. It should be noted that all equations presented to this point yield impingement current per beamlet \( [J_i] \). The total

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<td>Source-Neutral-Expansion Length ( [\ell_n] )</td>
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### Table 2

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### Experimental Results

#### Neutralization Lengths

Emissive probes are commonly used to determine potentials of plasmas having densities greater than ~10^9 cm^-3; however, their use in electron-deficient environments like those near grid sets of ion thrusters is not common and is more difficult. However, Smith et al. developed a technique called the Inflection-Point Technique (IPT) which can be used in these environments. The method (as used in this study) involves measuring the current drawn to or emitted from a hot-filament emissive probe as its potential is swept over a range from below to above the potential of the local environment. When the probe potential is greater than the local potential it emits electrons to and collects ions from the surroundings and when the probe potential is lower than local potential it collects electrons (if they are present) from the surroundings. Because the probe can emit electrons readily, the curvature of the probe-current-v.-voltage trace changes at the local potential making this potential identifiable. The only disadvantage of this method is that it is time consuming. To obtain potentials from which \( \ell_n \) can be determined (like those presented on Fig. 4), the emissive
probe is positioned at a discrete axial and radial position, current/voltage data are collected and then later analyzed to determine the local potential. This procedure must be repeated at several axial positions until sufficient data are obtained to determine \( \ell_n \). Relevant data can also be obtained quickly by sensing the floating potential of a hot emissive probe as it is swept axially from a point several centimeters downstream to a grid aperture. When both techniques were used with the 7-hole, 1-cm grid set typical results like those shown in Fig. 7 by the solid line (floating potential) and data symbols (IPT) were obtained. While the floating potential data do not match true local potential obtained using the inflection-point method at locations close to the accel grid, the values obtained further downstream agree quite well. Most importantly, both sets of data show a rather sudden decrease in potential at 0.6 cm (labeled the floating-potential-break point) thereby suggesting that either method can be used measure the distance from this point to the accel grid yielding \( \ell_n \). This result is important for this study because it shows that \( \ell_n \) can be determined using the relatively simple procedure of measuring the axial variation of the floating potential and identifying the location at which the slope rather suddenly changes from near zero to a positive value.

Values for \( \ell_n \) determined using this procedure have been measured and compared to those obtained using the Kerslake model over a wide range of operating conditions. Figure 8 shows the effects of varying the beam current from 0.25 to 3.75 mA on \( \ell_n \) for the SERT II thruster equipped with the 7-hole, ½-cm grid set and operating at the conditions presented. The experimental values for \( \ell_n \) are shown by the circular data points and the solid line represents values predicted by the Kerslake model (Eq. 9). The experimental data show that \( \ell_n \) is relatively constant at an asymptotic value near -0.5 cm for higher beam current (above 1.5 mA). A comparison of the circular data and the solid line shows that both the experimental and predicted values for \( \ell_n \) agree very well.

The effect of screen-grid potential, over the range 600 to 1600 V, on \( \ell_n \), is presented on Fig. 9. Again the circular data points are the experimentally measured values and the solid line represents values computed using the thruster conditions and the Kerslake model. The experimental data show some scatter, however, in general they tend to follow the trend of the predicted values in that they increase slightly as the screen-grid potential is increased. Similar data showing the effect of increasing the accel-grid potential from -1600 to -300 V on \( \ell_n \) are presented on Fig. 10. These experimental data show that as the accel-grid potential is increased, \( \ell_n \) linearly decreases from 1.25 to 0.25 cm. The Kerslake data presented on the figure also show a decrease in \( \ell_n \) with increasing accel-grid potential, however, they show some curvature and a less-negative slope compared to the experimental data. Both data
sets do, however, predict $I_n$ values which are of comparable magnitudes, so the agreement between them is also considered to be good.

The effect of changes in the ambient xenon density induce on $I_n$ were determined by operating the SERT II thruster at a constant condition (given on Fig. 11) and introducing xenon 2.7 m downstream from the thruster to increase the background atom density. The circular data points on the figure show that as the density was increased from $2.5 \times 10^{11}$ to $4.5 \times 10^{11} \text{ cm}^{-3}$, $I_n$ remained constant at 0.48 cm and this result agrees with the value predicted by the Kerslake model (0.49 cm). Experiments were also performed to determine the effect of changes in the neutralizer bias voltage and keeper current on $I_n$. The measured (circular points) and the predicted values (solid line) show that as the density was increased introducing xenon thruster at a constant condition (given on Fig. 11) and maintaining a constant xenon density (approximated as the beam current divided by the dimensional-neutralization length $L_{n, 300}$). The experimental data obtained for the: 1) 7-hole, $\frac{1}{3}$-cm-grid set (the circular data points), 2) 7-hole, 1-cm-grid set (the square points), and 3) 15-cm SHAG set (triangular data points) are presented on Fig. 14 along with the Kerslake values (the solid line, Eq. 13). This figure shows that the circular data points agree very well with the predicted values over the entire perveance range investigated, the square data points agree well for perveance values above 0.5, and the triangles agree for perveance values below 0.25. In general however all the data presented agree fairly well with the predicted values for $I_n$. Direct comparison of $I_n$ and normalized perveance-per-hole obtained from the Kerslake model with results from the three grid sets as either the screen- or accel-grid potentials vary becomes inconvenient because both normalized perveance-per-hole and the net-to-total voltage ratio $[R]$ vary. To eliminate this problem both sides of Eq. 9 were multiplied by the square root of the current density (approximated as the beam current divided by the
grid area) eliminating the dependence of the Kerslake model on beam current and allowing direct comparison between the three grid sets. The effects of varying the screen-grid potential from 500 to 1600 V on this parameter are presented on Fig. 15 for the two, 7-hole-grid and the SHAG sets. The circular points correspond to the 7-hole, ½-cm grid data, the square ones to the 7-hole, 1-cm data, the triangles to the SHAG set and the solid line to the predicted data. This figure shows that the experimental data for the 7-hole-grid sets compares well in magnitude but not trend with the predicted values and the 15-cm-SHAG data agree well in trend but not in magnitude. Presented on Fig. 16 are the effects of varying the accel-grid potential from -1600 to -300 V where again the circles are the 7-hole, ½-cm data, the squares the 7-hole, 1-cm data, the triangles the 15-cm-SHAG data, and the solid line the predicted values. This figure shows the experimental data follow similar trends as the accel potential is varied over the aforementioned range although the SHAG data and some of the 7-hole, ½-cm data are 30 to 50% greater than values predicted by the Kerslake model.

**Impingement-Currents**

All of the data presented so far have shown the effects of varying thruster operating and design conditions as well as neutralizer operating parameters on $I_n$. It is, however, the effect of these parameters on the measured impingement current and their agreement with computed currents (Eq. 8) that is of primary interest. Figure 17 is a comparative plot showing measured and computed impingement currents as a function of beam current for the SERT II thruster operating at the conditions given in the legend. The data of this figure show that increasing the beam current from 0 to 3.5 mA causes the measured impingement current (open circles) to increase linearly from 0 to 60 μA where upon direct impingement causes the measured-impingement current to increase dramatically. The solid circles presented on the figure are the computed impingement-current-v.-beam-current data obtained using measured values of $I_n$ (from Fig. 8) and they show excellent agreement with the measured currents below the onset of direct impingement. The solid line on Fig. 17 shows impingement currents computed using the Kerslake-model values for $I_n$ and they agree well with both the open and solid circles. Figure 18 presents impingement-current-v.-beam-current data obtained using the 7-hole, 1-cm grid set which show that the measure impingement current (open circles) increase linearly from 25 to 75 μA as the beam current is increased from 0.75 to 3.0 mA. Beyond this, the figure shows that direct impingement occurs. The solid, circular points are the impingement current values computed using measured $I_n$ data and the solid line is the current obtained using $I_n$ values from the Kerslake model. As
expected, this figure shows excellent agreement (within 20%) between the measured and computed impingement currents. The linear variation between \( J_B \) and \( J_i \) if the source-dominated-impingement current is the major component of the impingement current. The fractional variation between \( J_B \) and \( J_i \), however, suggest that the background-dominated-impingement current is the major component. To determine if the background-dominated-impingement current is the major component when the 7-hole grid sets are used, and the variations in propellant utilization are to small too see any effect, the fractions of the total-impingement current due to both the source- and background-dominated components were calculated using the Kerslake values for \( I_H \) (from Fig. 8) and the results are plotted on Fig. 20. This figure suggests that for the 7-hole, 1/2-cm-grid set, which has an exposed accel-grid diameter of 5.5 cm, the production of charge-exchange ions is source dominated. In contrast, the impingement-current fractions presented on Fig. 21, which were computed for the SHAG set having an exposed accel-grid diameter of 15 cm, show that the background-dominated-impingement current is responsible for the majority of the impingement-current ions. Thus, the combination of the larger exposed accel-grid area and the higher background pressures associated with the 15-cm-SHAG set causes a fundamental change in the dominate impingement-current component. It is noted that the source-dominated impingement current fraction presented on Fig. 21 may be too low because the assumptions used to perform the Monte-Carlo simulations neglect the effects of adjacent apertures. Therefore, the 7-hole grid sets this assumption only introduces slight errors but they are much greater for the 15-cm-SHAG set. More accurate simulations of the propellant flow through the 15-cm-SHAG set may result in impingement-to-beam-current ratios more typical of those measured on mercury thrusters (i.e. 0.25 to 0.5%).

**Fig. 19** Effects of Beam Current on Impingement Current for the 15-cm SHAG set

An interesting observation related to the data of Fig. 19 is that the measured impingement current should vary as \( J_B(1 - J_B/\mu) \) if the source-dominated-impingement current is the major component of the impingement current. The linear variation between \( J_B \) and \( J_i \), however, suggest that the background-dominated-impingement current is the major component. To determine if the background-dominated-impingement current is the major component when the 7-hole grid sets are used, and the variations in propellant utilization are to small too see any effect, the fractions of the total-impingement current due to both the source- and background-dominated components were calculated using the Kerslake values for \( I_H \) (from Fig. 8) and the results are plotted on Fig. 20. This figure suggests that for the 7-hole, 1/2-cm-grid set, which has an exposed accel-grid diameter of 5.5 cm, the production of charge-exchange ions is source dominated. In contrast, the impingement-current fractions presented on Fig. 21, which were computed for the SHAG set having an exposed accel-grid diameter of 15 cm, show that the background-dominated-impingement current is responsible for the majority of the impingement-current ions. Thus, the combination of the larger exposed accel-grid area and the higher background pressures associated with the 15-cm-SHAG set causes a fundamental change in the dominate impingement-current component. It is noted that the source-dominated impingement current fraction presented on Fig. 21 may be too low because the assumptions used to perform the Monte-Carlo simulations neglect the effects of adjacent apertures. Therefore, the 7-hole grid sets this assumption only introduces slight errors but they are much greater for the 15-cm-SHAG set. More accurate simulations of the propellant flow through the 15-cm-SHAG set may result in impingement-to-beam-current ratios more typical of those measured on mercury thrusters (i.e. 0.25 to 0.5%).

**Fig. 20** Effects of Beam Current on the Background- and Source-Dominated-Impingement Current Fractions for the 7-hole, 1/2-cm Grid Set

**Fig. 21** Effects of Beam Current on the Background- and Source-Dominated-Impingement Current Fractions for the 15-cm SHAG Set

**Conclusions**

Data presented within this paper have shown that ions which impinge on the accel grid are produced predominantly by charge-exchange collisions and not by either single- or multi-step-electron-impact ionization. In addition, the data show that the length of the downstream region from which all charge-exchange ions impinge on the accel grid \( f_{\text{ex}} \) can be determined by sensing the axial-floating potential profile using a hot-filament, bent emissive probe. However, if accurate potential values are required in this region the Inflection-Point Method must be used to measure them. Neutralization lengths \( f_{\text{ex}} \) measured over a wide range of operating conditions (beam current, grid potentials, background atom density, neutralizer bias voltage and keepcr current) using three different grid sets were shown to agree well with values predicted using a model presented by Kerslake.

Potential data were presented that suggest ions created downstream of \( f_{\text{ex}} \) can reach the accel grid because no potential ridge exists to prevent their upstream migration through potential-trough regions that exist between adjacent ion beamslets. Based on this observation, a simple 1-D model was shown to predict measured impingement currents with good accuracy (±30%). The model reflects two
contributions to the impingement current; namely source-dominated and background-dominated impingement currents. The source-dominated impingement current is a direct consequence of thruster operation and can not be eliminated, however, the background-dominated component is a consequence of the finite, vacuum-facility pumping speed and should be small in high-vacuum environments. The magnitude of the background-dominated-impingement current component can be estimated by using an effective charge-exchange-ion-extraction length which is equal to 1/4 of the exposed accel-grid diameter. Computed, impingement-current data presented for the SERT II ion thruster equipped with the 15-cm-SHAG set show that the higher-than-expected impingement-to-beam-current ratio (2 to 3% for the operating conditions presented) is primarily due to charge-exchange ions created through collisions between beamlet ions and background atoms. This suggests that if the same tests were conducted in a facility having a high-pumping speed, impingement-to-beam-current ratios similar to those obtained for mercury thrusters could be obtained.

Acknowledgements

This work was supported by the NASA Lewis Research Center under Grant NAG3-1206. This financial support and the technical support, suggestions and comments of the grant monitor, Mr. Vincent K. Rawlin, are gratefully acknowledged. In addition the authors would like to thank Mr. John Dolaghan for providing and running the Monte-Carlo simulation program used to generate the neutral-density-profile data presented.

References


