ELECTROSTATIC ION THRUSTER OPTICS CALCULATIONS*

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Two- and three-dimensional ion thruster optical calculations including both source and exhaust plasmas are performed. These calculations include both a self-consistent ion source extraction plasma sheath and an explicit computation of the primary ion optics including sheath and electrode-induced aberrations. A study determining the effects of beam space charge, accelerator geometry, and properties of the downstream plasma sheath on the position of the electrostatic potential saddle point near the extractor electrode is made. Results of the electron blocking potential barrier height as a function of electrode thickness and secondary plasma processes are described. The plan of this study is to provide preliminary considerations (Section 1), compare with the results of Aston for various perveances (Section 2), compare with the results of Homa for various perveances and secondary plasma potentials (Section 3), examine the effect of accelerator electrode thickness on blocking potential (Section 4), examine the effect of space charge on blocking potential (Section 5), examine the effect of secondary plasma potential and space charge on secondary ions from the exhaust plasma (Section 6), illustrate a 3-D calculation (Section 7) (Section 1-6 were in 2-D).

1. General Considerations for Primary Ion Optics

Ion thrusters consist of a large plasma chamber with many extraction holes and acceleration channels. One of these extraction/accelerators is shown in Fig. 1.1. From left to right in this figure, one can see the plasma chamber, the screen electrode, and the accelerator electrode. In this example, we used a total accelerating voltage of 600 V and a retarding voltage of 180V, giving a net-to-total accelerating voltage ratio R of 0.70. On the left-hand side of the figure is the source plasma and on the right-hand side is the downstream plasma. The lines going vertically are the equipotential contours shown by themselves in the lower part of the figure. The dense lines on the left-hand side of the figure correspond to the plasma sheath. The ion trajectories (mostly horizontal lines) are shown going from left to right. Aberrations produced on the edge of the plasma sheath can be seen. Another sheath is formed when the ions leave the thruster, which greatly affects the trajectories of the positive ions and electrons in the downstream plasma.

A general consideration is the effective acceleration length, l_e' . This is defined in various ways by Aston¹ and Homa,² whose experiments will be compared in Sections 2 and 3. In each case, it was deduced from a geometric construction and is independent of perveance. For the geometry considered in Section 2 (Aston), the calculated value of l_e' as described by

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Aston, l_e^A , and Homa, l_e^H , is shown in Fig. 1.2. The "actual" acceleration length as deduced from calculations is also shown (the lower part of Fig. 1.1 is a subset of these cases for illustration). It is deduced by measuring the distance, on axis, from the onset of the sheath to the saddle point (upper bound) or the plane of the upstream surface of the accelerator electrode (lower bound). The effective acceleration length is a strong function of perveance since the sheath changes shape significantly over this density range. The so-called transverse space-charge limit (TSCL) which denotes the onset of primary ion interception with the accelerator electrode (in the zero temperature limit) is indicated by the vertical line. Of course, there is no space-charge limit in the Child-Langmuir limit (where a potential hill forms to turn the ions around) since the electrons from the source plasma would immediately negate any hill that was about to form.

The TSCL for the Aston geometry is illustrated in Fig. 1.3. If one were to increase the plasma density in the ion source, thereby making available more ions for extraction, one may expect more ions to be extracted. This ideal expectation is shown by the straight line labeled ideal, in the figure. However, there are deviations from this ideal everywhere. For low densities, illustrated in Fig. 1.4(a), more ions get out because the plasma sheath is so concave inward towards the ion source that more ions are attracted to the accelerator than would be expected from geometrical considerations, see Fig. 1.4(b). This case is denoted in Fig. 1.3 by the point at $j_p = 5 \text{ mA/cm}^2$. For higher plasma densities, this plasma edge concavity does not occur at higher densities. As illustrated by the case, $j_p = 20 \text{ mA/cm}^2$ shown in Fig. 1.1, the ions are attracted toward the screen electrode - the plasma shielding them from the accelerator. Not many trajectories are so affected but those that are count more since they are the outer ions in cylindrical geometry.

At yet higher perveance (plasma density), the ions begin to intercept the accelerator electrode as the TSCL is reached. An extreme case, at $j_p = 40 \text{ mA/cm}^2$, is illustrated in Fig. 1.4(c). The situation is worse than appears at first sight for three reasons. One, since the geometry is cylindrical the intercepting ions count more than the trajectory lines would indicate. For example, about half of the extracted ions hit the accelerator electrode in the illustration shown. Second, the impinging ions cause sputtering of the accelerator electrode, decreasing longevity. Third, secondary electrons are emitted from the electrode as a result of the ion bombardment; these secondary electrons travel down the accelerator (toward the left) and cause further damage. Needless to say, such overdense operation is to be avoided. Finite ion temperature causes the onset of accelerator electrode interception to occur more gradually, beginning at a slightly lower perveance.

2. Comparison with the Experimental Data from Aston

A comparison between the data of G. Aston¹ and the present calculation is shown in Fig. 2.1 [Fig. 2.2 shows the geometry for the situation labeled in Fig. 2.1]. Aston's data is represented by the triangles in which the primary ion beam envelope is shown as a function of normalized perveance. How accurate the measurements can determine the beam envelope is not clear; the limit at high perveance is due to beam interception. Our calculations are shown by the circles; the upper curve represents the beam envelope with error bars reflecting statistical error due to finite number of ions considered. We assume zero initial ion temperature; this assumption will underestimate the beam divergence at some perveance where ion temperature might dominate the beam optics. The comparison between the theory and experiment is perhaps the best that may be expected given finite, but

unstated errors in the experimental determination of the beam envelope (producing a lower bound) and systematic errors in the theory due to zero ion temperature. Also an RMS calculated beam divergence

$$\theta_{rms} = \sqrt{\theta^2 - \theta^2} \quad (1)$$

is shown by the lower circles in Fig. 2.1. For low values of perveance the experiment lies between the RMS calculation and a rather refined calculation of the beam edge. At high values of perveance, the ion temperature may dominate making the experiment higher than the calculations (which assumed zero temperature). The transverse space charge limit determined by beam interception is virtually the same for the theory and the experiment as evidenced by the maximum perveance reached.

3. Comparison with the Results of Homa

The geometry considered by Homa² is shown in Fig. 3.1 For a particular value of voltage ratio R, we get similar results to those in the previous section (Fig. 3.2) if we use the same excuses for the differences between the interpreted experimental and theoretical results. Other values of R were considered by Homa (his data are reproduced as Fig. 3.3) Modeling comparisons for various values of R are shown in Fig. 3.4 indicating the well known diverging lens effect that the accelerator electrode has when it is at a negative extremum potential (the lens becomes stronger when R is decreased).

In contrast to Figs. 3.2, 1.2, and 2.1, error bars were not explicitly placed on the modeling results of Fig. 3.4. The precise meaning of the words "beam divergence," and errors associated with the experimental points associated with that meaning, are not stated for the results of Fig. 3.3 or 2.1.

4. Effects of Accelerator Electrode Thickness (T) on Blocking Potential

It is important to have a saddle point in the potential distribution, as shown in Fig. 1.1 and 2.2, so that electrons generated in the downstream plasma cannot go directly down the accelerator column. However, collisions between positive ions from the downstream plasma and the accelerator electrode can produce secondary electrons which can then proceed down the accelerator column. The effect of varying the thickness of the accelerator electrode on the position and strength of an electrostatic saddle point occurring in the vicinity of the accelerator electrode is calculated.

One advantage of using a thicker accelerator electrode is that a lower retarding voltage is required to prevent secondary electrons from going down the accelerator gap. This allows ions from the exhaust plasma that intercept the accelerator electrode to impact at a lower velocity. This lower velocity reduces heat loading and also reduces the number of secondary electrons subsequently kicked out of the electrode. Secondary electrons generated from the accelerator electrode (from bombardment by positive ions) are also reduced since many of these exhaust electrons re-enter the secondary plasma instead of going down the accelerator column. The accelerator electrode can be shaped to maximize this effect for a thick accelerator electrode the source can operate with less gas (fuel) throughput. The disadvantage of a thick accelerator electrode is that the gas pressure in the accelerator

column is higher, thereby producing more secondary ions from charge exchange and ion-electron pairs from impact ionization.

The threshold blocking potential as a function of electrode thickness is shown in Fig. 4.1. The threshold potentials shown in Fig. 4.1 are calculated for typical beam currents and permeances. At these beam currents, the beam itself will suck electrons into it and allow them access to the accelerator column; this may occur even for very large electrode thickness as evaluated in Fig. 4.1 by the "beam space charge asymptote" (BSCA). The BSCA is the potential in the beam due to its own space charge, that would attract electrons from the exhaust plasma regardless of the accelerator electrode thickness; it does depend on the electrode radius. If, on the other hand, space charge is neglected but somehow one managed to get a potential between the exhaust region and the accelerator electrode then the threshold potential will be essentially zero. This case, of academic interest only, is also shown in Fig. 4.1 denoted by $\lambda_D \gg T$. These considerations are illustrated explicitly in Section 5.

5. Effects of Space Charge on Blocking Potential

The position and shape of the secondary plasma on the right-hand side of Fig. 2.2 depends upon the downstream exhaust plasma density. The downstream exhaust plasma is generated by the beam ions, residual gas, and electrons that are deliberately created to prevent spacecraft charging. The downstream exhaust plasma density is expected to be only a small fraction, perhaps 3% or less, of the ion source plasma density. If the downstream exhaust plasma density is higher than this, then this sheath will become thinner. For example, the left-hand side of Fig. 2.2(b) [vs Fig. 2.2(a)] shows a thin sheath corresponding to the high plasma density in the ion source. The effect of varying the downstream plasma density in a particular case is shown in Fig. 2.2. In Fig. 2.2(a), the secondary plasma is assumed to be 1/64th of the primary ion plasma density and in Fig. 2.2(b) it is assumed to be one-eighth of the source plasma density. As can be seen, there is only a small effect on the saddle point; the presence of a secondary plasma has only a small effect on the potential hill for electrons coming from the right.

The threshold blocking voltage vs accelerator electrode thickness is shown in Fig. 4.1. As indicated in Fig. 5.1, increases of the electrode thickness beyond $T = 4$ have little effect on the space charge hill due to beam space charge which provides an attraction for the exhaust plasma electrons, allowing them to migrate toward the accelerator column even for very thick accelerator electrodes.

The finite threshold blocking voltage for large T , shown in Fig. 4.1, is due to beam space charge. To illustrate this effect three cases are considered in Fig. 5.1 for a $T = 4$ accelerator electrode thickness. The first case, Fig. 5.1(a), is with no space charge. As long as the accelerator electrode potential, ϕ_a , can be held negative with respect to the exhaust "plasma" potential, ϕ_2 , a potential barrier will build up equal to $|\phi_a - \phi_2|$. If the Debye length, λ_D , is high enough (the secondary plasma density low enough) the potential hill is equal to $|\phi_a - \phi_2|$ for all T such that $\lambda_D \gg T$. Including the effect of beam space charge produces the result shown in Fig. 5.1(b) where the potential hill is reduced almost to zero. Addition of the secondary plasma [Fig. 5.1(c)] does not alter the potential hill significantly (this case is very near threshold and is a data point in Fig. 4.1). Since it is desirable to reduce the secondary

plasma positive ion impact to less than 100 volts but not produce too much gas loading, a thickness of 2.5 appears warranted.

6. Effects of Secondary Plasma Potential and Space Charge on Secondary Ions from the Exhaust Plasma

In the absence of space charge, for a case where $R \cong 0.5$ (Aston geometry), the motion of secondary positive ions (if there were any) follows as in Fig. 6.1. Many of these ions overshoot the accelerator electrode as shown and when they have gone uphill as far as they can go, they return downhill and can strike the accelerator electrode from the acceleration side as shown. Secondary electrons can then be produced from these ion interceptions and such secondary electrons would all go down the main accelerator column with deleterious consequences. While the voltage between the exhaust plasma, in this case considered on the right-hand boundary of the figure, and the accelerator electrode is kept high to prevent exhaust plasma electrons from directly falling down the accelerator column, it can be seen that making this potential too high can make the positive ions do more damage (they hit with higher velocity and unleash more electrons). The presence of beam space charge and plasma fields alters the picture significantly as is shown in Fig. 6.4 (for the same R values). The primary ions tend to drive the secondary ions off to the side, meaning that far less of them get to overshoot the accelerator electrode. However, a new mechanism for focussing these positive ions is presented by the nonuniform deposition as shown. Lowering the secondary plasma potential differences (increasing R), as illustrated in Fig. 6.3 and 6.4, does not in and of itself mitigate this tendency for ion focusing (although the velocity is lower so they do less damage).

A higher density for the exhaust plasma reduces the range and strength of the beam forces as can be seen in Fig. 6.5. It is highly likely that ring focusing such as shown in Fig. 6.2 - 6.5 is taking place for a wide variety of situations. Since the focus is a function of the perveance of the secondary plasma ions, a mitigation of such focusing may take place if the exhaust plasma has a time varying density. This can be produced by varying the exhaust filament current in time. Alternatively, it may be thought that an oscillation of the secondary plasma density naturally takes place. Under this condition, it is likely that the brunt of the ion focusing will occur at the vertices of the web since there is a three-fold multiplicity in beam intensity at that singular location. The practical solution may be to just make the electrode thicker near the center of the web by drilling conical-sided holes instead of right circular cylinders.

7. Three-Dimensional Calculations

The calculations presented above are in 2-D cylindrical geometry. However, for ion thrusters with dished electrodes it is desirable to effect a transverse aperture displacement which will steer the beam. In addition, it may be desirable to consider in detail the adjacent beamlets and apertures, neither of which exhibit cylindrical symmetry. It may also be desirable to account for a globally nonuniform plasma, either the source or exhaust plasma, which generally will not exhibit a radial symmetry, at least not about the axis of an edge beamlet.

Three-dimensional calculations are necessary to model such effects. Figure 7.1(a-c) shows the results of a 3-D calculation where the accelerator electrode has been displaced with

respect to the screen electrode. In Fig. 7.1(a) the configuration on the symmetry plane can be seen, which is somewhat analogous to Fig. 1.1. In Figs. 7.1(b) and 7.1(c) the full 3-D representations of this particular example are shown. The displacement of the electrode is obvious in Figs. 7.1(a) and 7.1(c). Fig. 7.1(b) shows an end view from the source plasma side showing the basic circular geometry of the electrodes. We intend to apply this 3-D analysis to the issues examined in the previous section.

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FIGURE 1.2

ASTON CONFIGURATION

FIGURE 1.3

7510N
HIGH PERVEANCE

1.4 C, D

FIGURE 2.1

FIG
2.2A

$$V_2 = \frac{h_1}{64}$$

FIG
2.2B

$$V_{12} = \frac{V_1}{8}$$

ACCELERATOR
ELECTRODE

PRIMARY
PLASMA

SCREEN
ELECTRODE

SECONDARY
PLASMA

FIG. 2

TOP
R=0.7

PRIMARY
PLASMA

due to
beam
edge

SECONDARY
PLASMA

↑
SCREEN
ELECTRODE

↑
ACCELERATOR
ELECTRODE

Secondary plasma
sheath

FIG 3.1

FIGURE 3.2

Effect of Net-to-Total Accelerating Voltage Ratio on Divergence

(Taken from "Ion Beamlet Steering for Two-Grid Electrostatic Thrusters,"
NASA CR-174671, 1984)

FIGURE 3.3

FIGURE 3.4

FIGURE 4.1

V=320

Fig 6.2

$D = 1/10$

V=160

F166.3

$P_2 = 1/32$

V=80

F166.4

$P_2 = 1/32$

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