The Influence of Charge-Exchange Ions on the Beam Divergence of an Ion Thruster

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It has been shown, using Faraday cup probes of different sensitivities to characterise the beam of the T5 gridded ion thruster, that the calculated beam divergence varies with probe type and analytical technique employed. This effect is due to the failure of less sensitive probes to detect energetic charge-exchange ions at large angles to the thruster axis. When included in the analysis, values of divergence are increased by an amount dependent upon thrust. Over the thrust range investigated, 0.3 to 25 mN, the contribution of wide angle charge-exchange ions rises rapidly at low thrust due to the decrease in propellant utilisation efficiency and the movement of the space-charge sheath into the discharge chamber plasma.

Introduction

This paper considers the influence of charge-exchange reactions within the grid system on the effective beam divergence of a gridded ion thruster. This parameter has usually been evaluated by sweeping a suitable probe through the exhaust to measure the flux of high energy ions as a function of angle. Subsequent data analysis has then yielded the semi-angle containing a specified proportion of the beam, and this has been defined as the divergence. Normally this proportion is 95%, but sometimes other values are quoted, such as 90%.

This procedure intrinsically assumes that the complete beam is sampled by the probe out to sufficiently wide angles to ensure that all high energy ions are included. This is not always the case, with many reported measurements extending out to perhaps 15 or 20 degrees only. Thus any peripheral ions are ignored and the resulting errors cause the quoted divergence to be less than the correct value. Similarly, the use of a relatively insensitive probe causes the effect of the low ion flux at wide angles to be under-estimated. In evaluating the overall performance of a thruster, the influence of these measurement deficiencies must be taken into account.

Under normal circumstances, where a thruster is operating at high thrust density, a probe of moderate sensitivity will give reasonably reliable values of beam profile and divergence; the errors are perhaps 2 or 3 degrees. However, it has been shown in extensive measurements of the beam characteristics of the T5 Kaufman-type thruster [1] that this is not so at thrusts well below the nominal value.

These measurements, which were carried out at Aerospace Corporation and are reported in this paper, covered the thrust range 0.3 to 30 mN [2]. The wide angle ions are then of increasing importance and necessitate the use of a more sensitive probe and observations out to much wider angles. For example, the measurements on the T5 thruster extended routinely to 40 degrees from the centreline, with some data being acquired out to 66 degrees. To illustrate the sensitivity of the instrumentation, the Faraday cup probe [3] achieved 7×10^{-4} mA/m^2, rather than the more usual 0.1 to 0.2 mA/m^2. Similarly, the Langmuir probe used to characterise the background plasma [4] was sensitive to electron number densities of below 5×10^6 cm^{-3}.

This wider divergence effect cannot be explained fully by the simple acceleration of primary ions by the grid system. However, a detailed computational analysis [5,6] has shown that primary ions can suffer charge-exchange collisions with neutral atoms in travelling between the sheath at the edge of the discharge chamber plasma and the accelerator grid. The

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resulting slow ions are then accelerated by the applied electric field into the primary beamlet.

As discussed in this paper, the varied starting points of these ions causes them to have very different trajectories to those of the main beamlet, explaining the wide angle, low flux "wings" to the normally observed ion beam profile. These wings influence the calculated divergence because they occupy a large volume of space around the primary beam, so that their aggregate effect is significant.

Under normal circumstances, these wings are not detected by instrumentation having low sensitivity. However, the propellant utilisation efficiency falls as the thrust is reduced [2], causing the relative number density of neutral atoms to rise and all charge-exchange effects to become more significant. This is seen very clearly in the computer simulations and causes a substantial proportion of the measured increase in divergence with falling thrust. In addition, the sheath penetrates further into the discharge chamber plasma as the thrust reduces, adding to the volume in which charge-exchange reactions can take place. This extra sheath curvature also increases the divergence by modifying the trajectories of the primary ions; this effect is also considered briefly in the paper.

Definitions and Errors

As mentioned above, the definition of ion beam divergence of an ion thruster is conventionally the half-angle containing 95% of the primary energetic ion beam current, assuming that the complete emitting area of the grid system is sampled during the measurement of this parameter. However, this definition intrinsically assumes that the whole beam is sampled out to very wide angles with instrumentation that is sensitive enough to measure minute currents, which are of the order of 2 mA/m^2. If excessive noise is to be avoided, the measurement sensitivity should be at least an order of magnitude better than this, 0.2 mA/m^2.

If the measurement accuracy does not meet this requirement, the contributions to the total current at large angles are not detected and are not included in the calculation of divergence. This has an important impact on the result, because these ions occupy a large volume of space around the periphery of the main beam and their integrated flux is significant. Indeed, the situation is worse than this in most cases because the instrumentation is either not sufficiently sensitive to detect these peripheral ions or does not travel to wide enough angles from the thruster centre line to do so. It is then accepted that a Gaussian fit to the measured part of the curve will give the divergence. This widely adopted practice is inaccurate because the wide-angle contribution is ignored – but much of the information provided in the literature makes this erroneous assumption.

Another error often made in the calculation of divergence is to base the derived angle only on data within a single cross section through the ion beam. The actual value required must be based on the current density as shown on such a plot, integrated through a complete revolution about the axis of the thruster, again accentuating the influence of the peripheral ions on the quoted divergence angles.

Although this need for integration can be met by calculation, it must first be established that the beam is symmetrical about its axis to the required accuracy. This is usually the case for a gridded thruster in which adequate care has been taken in the design and fabrication of the grid system. Alternatively, a probe may be scanned across a series of transverse sections of the beam to establish the full profile in an unambiguous way, as was done originally by the Culham Laboratory in early assessments of the T5 thruster [7]. Alternatively, an array of probes may be used for the same purpose; an example is the beam characterisation of the RIT-10 radiofrequency (RF) ionisation thruster [8].

However, as far as is known, few measurements have approached the sensitivity required to establish the beam profile out to sufficiently wide angles to examine the effects on divergence of the peripheral high energy ions. Consequently, the ion probe system located at Aerospace Corporation [3] was developed specifically to provide the desired sensitivity. Indeed, this is nearly 4 orders better than specified above, with an ion probe current sensitivity of 10^{-13} A, which translates into a current density of 7×10^{-4} mA/m^2. Other existing equipments may be adequate at high thrust, where the peripheral ions have less effect, but are probably incapable of providing an accurate result from a 10 cm diameter thruster at, say, less than 10 mN.

T5 Thruster, Facilities and Instrumentation

T5 Ion Thruster

The experimental work reported in this paper was conducted using a standard T5 ion thruster [1], which is a 10 cm beam diameter Kaufman-type device employing solenoids to produce the magnetic

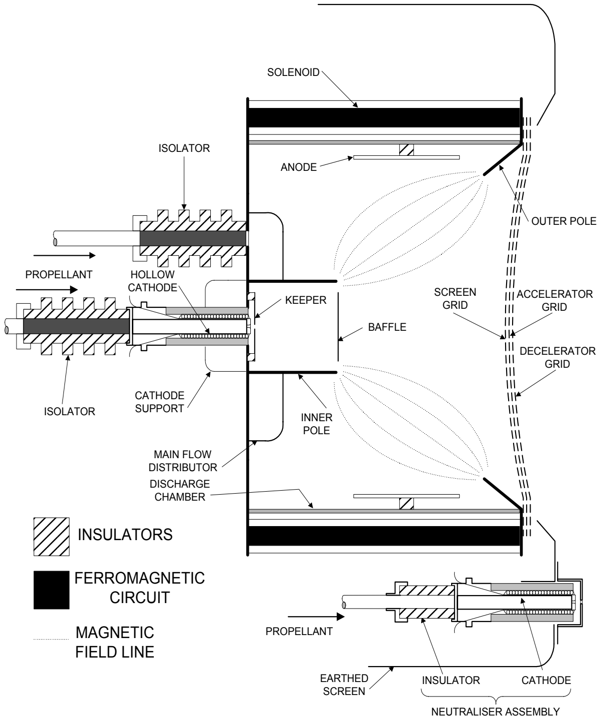

Figure 1 – Schematic cross sectional view of the T5 ion thruster.

field within the discharge chamber and separate propellant feeds to the hollow cathode, discharge chamber distributor and neutraliser. This distinct configuration, indicated in Figure 1, permits the achievement of smooth throttling over a very wide range [2], which extends from 0.3 to more than 70 mN. However, the work reported here was restricted to the lower part of this range, 0.3 to 25 mN.

Another feature of the thruster, which has a bearing on the beam divergence data reported here, is the use of concave dishing for the triple-grid system employed to extract and accelerate the ion beam. Dishing is required to ensure thermal stability of the grid system as the thruster warms up during operation, and can also be convex; the latter is, for example, used in the 30 cm thruster utilised successfully in the Deep Space 1 interplanetary mission [9].

Concave dishing tends to focus the beam, thereby ensuring that the divergence is relatively low. However, if the depth of dishing is sufficient to provide good thermal stability, the resulting focal point can be too near the thruster, the ion trajectories cross, and there is then the possibility of excessive divergence. This is prevented in the case of the T5 thruster by "compensation", in which the holes in the three grids are displaced slightly with respect to each other in a radial direction. This introduces the correct electrostatic deflection of each beamlet to yield the required overall divergence. Defined in the usual way, this can be as low as 8 deg [10].

Test Facilities

Most of the experimental work reported here was conducted at Aerospace Corporation using a test facility of 3 m diameter and 6 m length, which is shown schematically in Figure 2. This facility is evacuated by two 36 inch diameter cryopumps, aided by a liquid nitrogen cooled shroud, giving an ultimate vacuum of the order of 10^{-7} torr. As indicated in Figure 2, along each side of the main chamber are welded four 1 m long extension chambers of 0.8 m diameter, which were originally provided to connect with the inlets of large diffusion pumps. Although two pumps are fitted to each of 6 of these chambers, they were not used in the tests reported here.

In these experiments, the T5 Mk 4 thruster was mounted in one of these extensions, with the beam aligned along a diameter of the main chamber. An angled graphite-coated target or beam stop was mounted as shown in Figure 2, and various diagnostics were situated in the space between this and the thruster. Reference is made in this paper only to the results obtained from the Faraday cup ion probe.

Reference is also made below to results obtained from two facilities located at QinetiQ, formerly DERA, at Farnborough. The first of these, which was used for thruster characterisation over a wide throttling range, is of 1 m diameter and 3 m length. As shown in Figure 3, this horizontal section is welded to a vertical cylinder, also of 1 m diameter, to which are fitted the two cryopumps, of 12 inch diameter at the top and 36 inch diameter at the bottom. This 2 m high section includes the angled titanium target. The thruster under test is mounted centrally on the access door opposite the target.

Although this facility provides an excellent ultimate vacuum, the total pumping speed is less than that provided in the Aerospace Corporation chamber, so thrust levels beyond about 12 mN are not accessible. No diagnostics were employed in the characterisation tests undertaken using this facility, since these were available in the larger of the QinetiQ chambers.

The latter is of 2.2 m diameter and has a total length of 4.7 m. It is equipped with 8 cryopump cold heads which cool large panels shielded from radiated heat sources by liquid nitrogen cooled shrouds. In addition, two large turbo-molecular pumps are fitted. The pumping speed is about 400,000 l/s and the ultimate vacuum approximately 5×10^{-8} torr. The thruster under test is mounted at one end in a glass auxiliary chamber, fitted with a turbo-molecular pump, from which it can be moved on a rail system through a 0.5 m internal diameter gate valve into the main chamber. A cooled carbon beam target is provided at the other end. The overall facility length is 6.3 m.

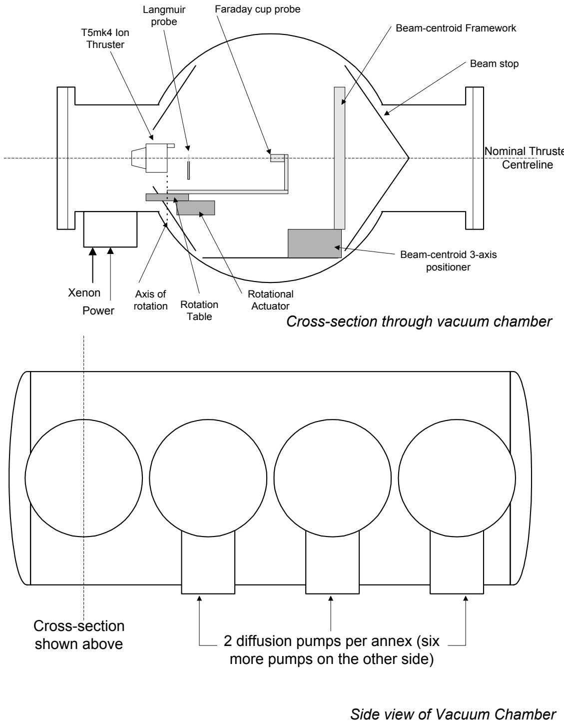

Figure 2 – Schematic diagram of the Aerospace Corporation test facility.

Diagnostics

The experiments reported here used Faraday cup ion probes [3] to measure the profile of the energetic beam ions, together with simple Langmuir probes [4] to explore the variation of background plasma density with position. Although many other diagnostics have also been employed [11], they are not relevant to the objectives of this paper.

The ion probe designed by Pollard [3] at Aerospace Corporation, shown schematically in Figure 4, operates in a conventional manner, although the method of excluding slow ions from the collecting electrode is unusual. Ions enter the probe via a 1 mm diameter collimating aperture, with electrons having been excluded by a fine stainless steel mesh covering the front of the instrument. This exclusion is possible without the application of a bias voltage because the plasma potential in the beam is typically 10 to 15 V above ground [4].

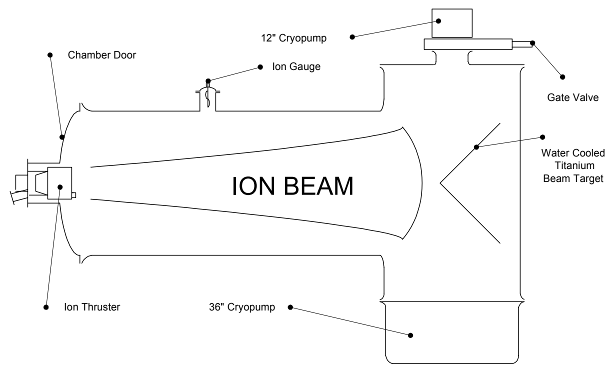

Figure 3 – Schematic diagram of the smaller QinetiQ test facility.

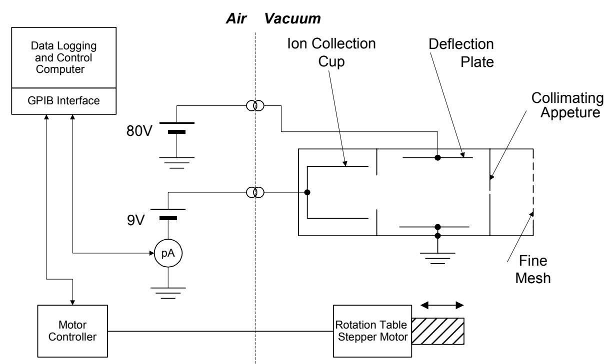

Figure 4 – Schematic diagram of the Aerospace Corporation Faraday cup probe.

In this design, the slow ions are removed from the internal beamlet by the application of a transverse electric field of about 90 V/cm, which is generated by applying a suitable potential to a pair of deflecting electrodes. The remaining ions are then collected by a central electrode biased negatively to ensure that secondary electrons do not escape.

As shown in Figure 5, this probe was mounted on a rotating arm, with the centre of rotation underneath the grid system of the thruster. The entrance aperture was located at a distance of 1.18 m from the grids, and was able to observe the complete exit area simultaneously. Thus no ions were excluded from the measurements.

In these experiments, the computer-controlled rotation was in 1 deg steps and covered the range –37 to + 66 deg.

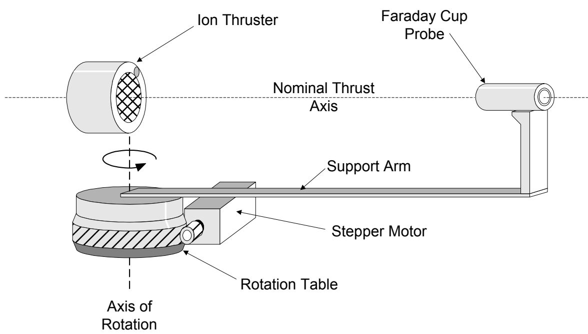

Figure 5 – Mounting arrangement for the Aerospace Corporation Faraday cup probe.

This configuration ensured that the probe was always aligned with the centre of the grids, thereby avoiding the problems associated with angled entry of the ions if a conventional traversing geometry is used, as was the case in earlier tests of the T5 thruster [7]. In that design, the probe axis was always parallel with the thruster axis. As a consequence, its traversal perpendicular to the latter axis caused the ions to enter at an angle to the probe axis, and this angle increased with movement away from the thruster centre line. This caused errors and complicated the subsequent data analysis.

The QinetiQ Faraday cup probe is more conventional, in that it uses a negative bias potential on the external metal mesh to assist in repelling the electrons from the beam plasma and slow ions are repelled from the collector by a relatively high positive potential. There are thus no internal deflection electrodes.

At Aerospace Corporation a conventional Langmuir probe was employed to measure the parameters of the beam plasma. The probe potential was swept in the usual way while recording the current drawn, and the thin sheath approximation was usually assumed in deriving electron temperature and number density [12]. A main requirement of these probe measurements was to confirm the complete symmetry of the ion beam, and this was fully accomplished [4].

Experimental Results

Characterisation

The thruster was characterised to some extent in all three facilities described above over the thrust range 0.3 to 30 mN, although data beyond 22 mN were obtained primarily in the tests at the Aerospace Corporation. Most of the work at the lower thrust levels was done in support of studies associated with the European Space Agency's (ESA's) Gravity and Ocean Circulation Explorer (GOCE) Mission [13], for which smooth throttling over a range of thrust of at least 10:1 is required.

To place the various parameters in context, the relationship between thrust and power consumption is shown in Figure 6. This relationship is close to linear, which is a useful feature for mission designers. To obtain this variation of thrust, the main parameters which are varied are the propellant flow into the discharge chamber and the anode current. Both are also reasonably linear with thrust. The magnetic field strength, as determined by the current through the solenoids, is used for fine adjustment.

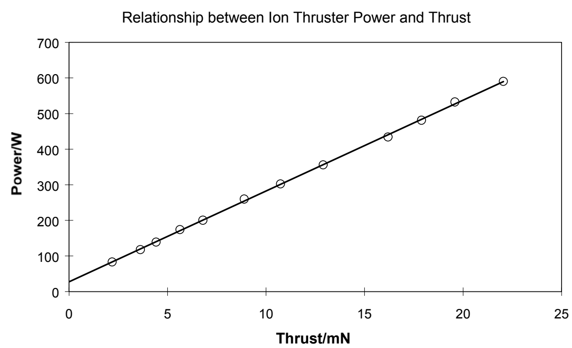

Figure 6 – Power consumption as a function of thrust.

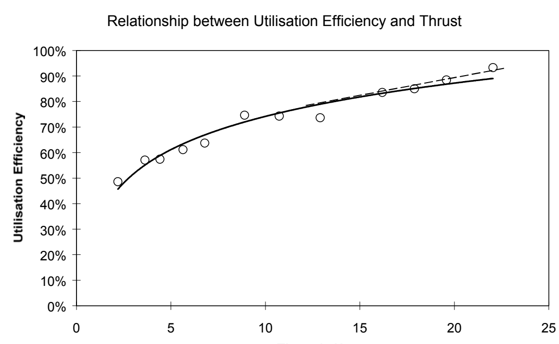

Figure 7 – Propellant utilisation efficiency as a function of thrust.

Another important parameter is the propellant utilisation efficiency, which is shown in Figure 7 and is relevant to the later discussion on the influence of charge-exchange ions on beam divergence. This is strongly non-linear owing to the relative increase in propellant losses as the degree of ionisation in the discharge chamber falls with decrease of thrust. In particular, these losses are influenced by the recombination of ions with electrons at the walls of the discharge chamber, which becomes more prevalent as the mean free path of the ions increases with fall in plasma density.

Faraday Cup Probe Results

The accuracy achievable with the Aerospace probe system is illustrated in Figure 8, which is for operation at 10 mN thrust. It is clear that the beam was symmetrical, that the data were noise-free and reproducible, and that meaningful measurements were available out to an effectively zero probe current. In this plot, the apparent current resolution was of the order of 20 mA/m^2. However, as will be seen later, the actual value achieved was several orders of magnitude better than this.

It should be noted that the peak current density did not coincide with the assumed geometrical axis of the thruster. This discrepancy, of 0.5 deg in this case, was ascribed to misalignments in the assembly of all elements of the apparatus.

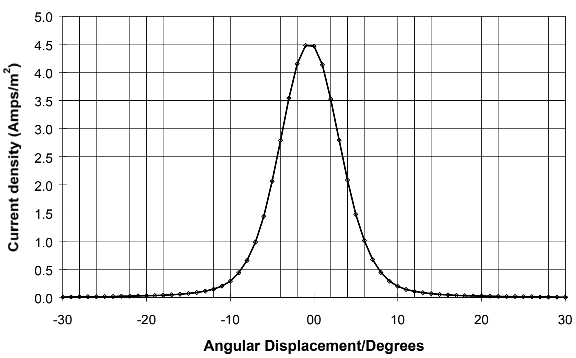

Figure 8 – Ion beam profile from the Aerospace Corporation Faraday cup probe at 10 mN thrust.

By summing the currents in concentric annular rings, and adopting the 95% of total current definition, the calculated divergence of this example was 21.4 deg. It should be noted that this was an accurate value, because the data extended well into the region of zero current (on the scale used in Figure 8), and all significant contributions to the beam were thus included.

Figure 9, shown for comparison purposes, is of the same thruster operating under identical conditions, but in the QinetiQ 2.2 m diameter test facility, when the available probe system more closely resembled the normal standard accepted in most laboratories. This was incapable of measuring the wide-angle contributions so essential to a precise evaluation of beam divergence, yet the data appeared to be of an excellent quality.

An evaluation using the Gaussian fit procedure mentioned above provided a divergence of 9.3 deg degrees. This is considerably below the value derived from the Aerospace data and gives a misleading impression of this very important thruster parameter. It should perhaps be emphasised here that similar erroneous values are often quoted in the literature for this reason.

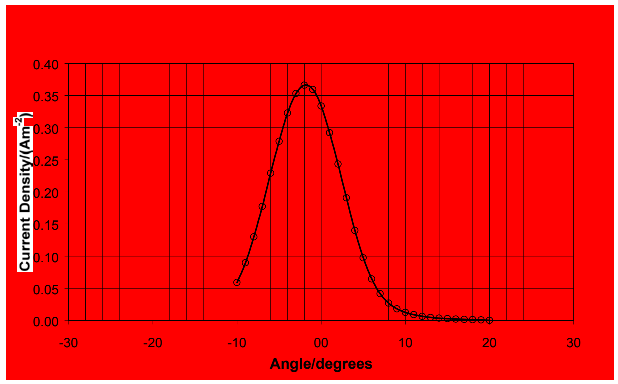

Figure 9 – Ion beam profile from the QinetiQ Faraday cup probe at 10 mN thrust.

To illustrate the sensitivity available from the Aerospace Corporation probe, the data acquired for Figure 8 are plotted on a logarithmic scale in Figure 10. It is clear that this probe system provided noise-free data out to the maximum angle investigated, 67 degrees. The sensitivity was much better than suggested above, and was certainly of the order of 10^{-7} to 10^{-8} A/m^2.

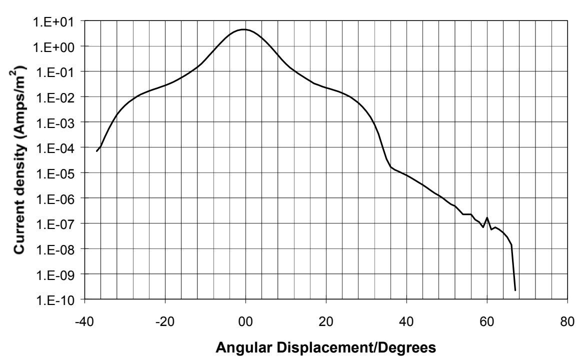

Figure 10 – Logarithmic ion beam profile from the

Aerospace Corporation Faraday cup at 10 mN thrust. With this higher sensitivity, the overall beam profile was very different to that shown in Figure 9 and the Gaussian distribution often assumed in calculations of divergence. The broad wings seen in Figure 10 were indicative of significant numbers of de-focussed ions, which were identified to be of charge-exchange origin. Clearly, they will not be observed unless a probe system of very high sensitivity is available.

Using the correct evaluation procedure and including all the measured data out to wide angles, the derived divergence is 21.4 degrees, as mentioned previously. This is indicative of an effect which becomes more pronounced as thrust is reduced.

The discrepancy between the true ion current variation with angle and that assumed in a Gaussian fit is emphasised in the graphical representation shown in Figure 11. In this the calculated annular current is plotted against angle for the two cases and it is clear that the discrepancy is becoming significant by about 7 deg. Thus the assumption of a Gaussian fit will certainly produce erroneous results.

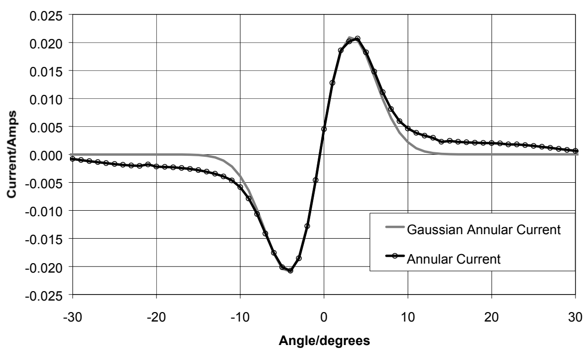

Figure 11 – Comparison between experimental annular ion current and that assumed in a Gaussian approximation.

In general, the wings on either side of the central peak of a typical probe trace were found to become much more pronounced as the thrust was reduced, and were eventually clearly visible at the current density resolution of Figure 8. As will be discussed later, this was due to an increase in the effects of the charge-exchange ions as the beam current was reduced.

This general observation is confirmed by examining the data shown in Figure 12 for 3.7, 4.7 and 5.7 mN. There the data are non-zero right out to 30 deg on either side of the axis, although the profile remains smooth, symmetrical and free of noise.

With this situation, the discrepancy between the two types of divergence analysis was much greater. Using the Gaussian fit approximation, the calculated divergence in the 4.7 mN case was 6.5 deg, whereas the precise analysis, utilising data out to an angle where the measured current density was essentially zero, gave 24.2 deg. Thus the former method provides a seriously erroneous answer, which could have important implications in some spacecraft designs.

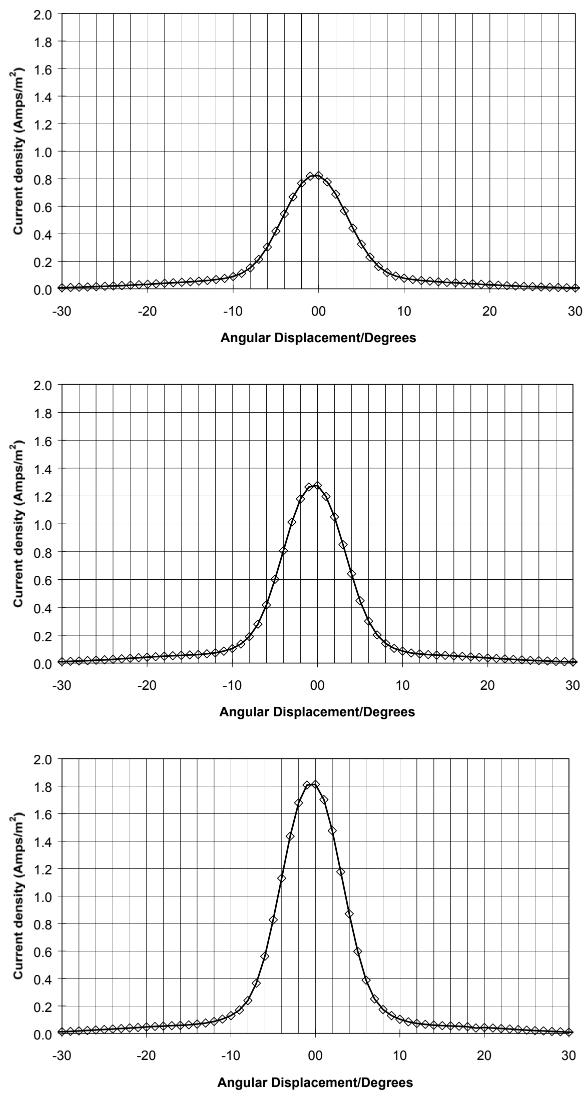

Figure 12 – Ion beam profile from the Aerospace Corporation probe at 3.7 mN (top), 4.7 mN (centre) and 5.7 mN (bottom) thrust.

This analysis was repeated for the thrust range 1.7 to 16 mN. The results are shown in Figure 12, which confirms that the discrepancy between the two analytical techniques is greatest at the lowest thrust, where the charge-exchange effects are most evident.

Also included in Figure 13, for completeness, is an indication of the thrust correction factor necessary to account for the precisely calculated divergence. This is small in all cases, being typically 0.980 at 16 mN and around than 0.960 at the lowest thrust.

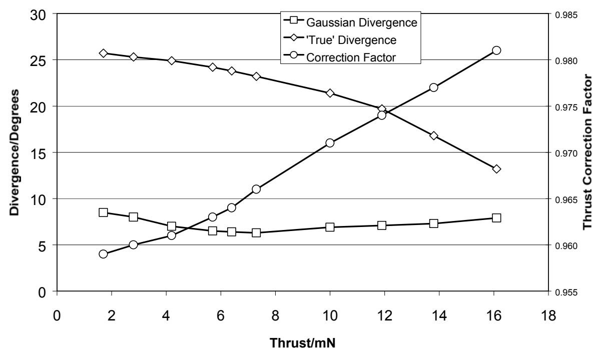

Figure 13 – Ion beam divergence for the two analysis techniques and thrust correction factor as functions of thrust.

Divergence Mechanisms

At least three mechanisms exist for the increase in beam divergence observed at low thrust levels. These all involve the production and acceleration of charge-exchange ions. They are:

- The influence of the changing electric field distribution within the grid system as the contribution to this field from the individual beamlets falls with decreasing thrust. This will modify the trajectories of the charge-exchange ions and may cause their divergence to increase.

- The increased production of charge-exchange ions, relative to the beam current, within the grid apertures at low thrust. This increase is due to the greater flux of neutral atoms, again in relative terms, owing to the decrease in propellant utilisation efficiency shown in Figure 7.

- The increased curvature of the screen grid plasma sheath at low current density and thus low thrust. It is likely that this will alter the trajectories of the emitted ions, resulting in greater divergence.

The clue to which one dominates is to be found in the shape of the ion beam profiles when measured very accurately at Aerospace Corporation. As reported above, these profiles changed in shape as the thrust was reduced, as can be seen from a comparison of Figures 8 and 12. The main beam was broadened very slightly at lower thrust, but the wings of the distribution rose very significantly, suggesting that the production of non-axial ions was considerably enhanced. This implies that the charge-exchange mechanism dominates, although the increasing curvature of the plasma sheath at the screen grid is likely to provide a further contribution.

Charge-Exchange Ions - Modelling

The explanation involving the charge-exchange mechanism is as follows. During their transit between the screen and accel grids, some primary ions suffer charge-exchange collisions with the residual neutral gas flowing from the discharge chamber. This results in the production of a high energy neutral atom and an ion with thermal energy. The latter is then accelerated by the electric field between the grids and becomes a part of the primary ion beam. However, it does not originate at the sheath at the edge of the discharge chamber plasma, as do most beam ions, and therefore follows a different trajectory. It is proposed that these ions constitute the bulk of the wide-angle part of the beam, as detected by the Aerospace Corporation sensors.

This effect has been simulated by the AEA Culham Laboratory SAPPHIRE software [5,6], with results which agree with the experimental data. This software has predicted successfully the flux and energy distribution of the wide-angle ions under various conditions, and examples are given below. It has also predicted the changing shape of the plasma sheath at the screen grid, and this is also consistent with increasing divergence.

It should be emphasised here that these effects are intrinsic to all grid systems and are not peculiar to any particular thruster. They cannot be avoided.

The influence of the upstream plasma density and beamlet current on the individual beamlet profile is evident in a comparison between Figures 14 and 15.

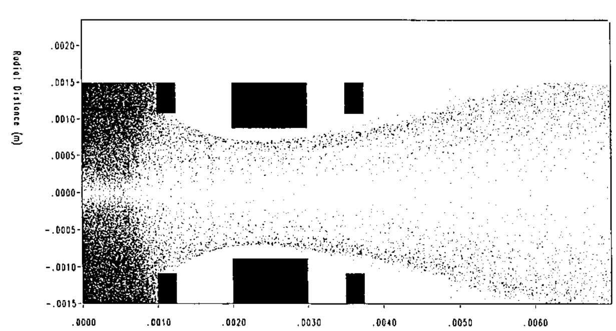

Figure 14 – Computed ion distribution within the grids

for $n_e = 3.5 \times 10^{11}$ cm^{-3}.

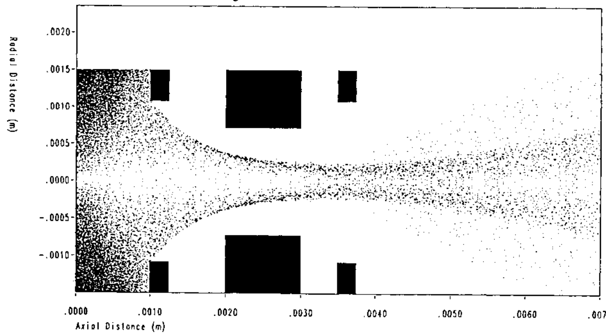

Figure 15 – Computed ion distribution within the grids for $n_e = 1.0 \times 10^{11}$ cm^{-3}.

The conditions in these two computed examples of the ion density distribution within the grids are identical, apart from the upstream electron number density, n_e, which is 3.5×10^{11} cm^{-3} in the former case and 1.0×10^{11} cm^{-3} in the latter. The electron and ion temperatures are 3.0 and 0.042 eV, respectively, and the upstream plasma potential relative to ground is 1180 V. The latter consists of an actual plasma potential of 40 V, plus the beam supply of 1140 V.

As well as a significant narrowing of the beamlet, it is evident that the lower plasma density in Figure 15 has resulted in the production of many more large angle ions. This is consistent with the increased divergence shown in Figure 13.

The actual trajectories of the charge-exchange ions can be computed with the SAPPHIRE software. An example is shown in Figure 16 for the higher value of n_e, 3.5×10^{11} cm^{-3}. This shows that many charge-exchange ions originate at or near the plasma sheath and that some of these follow widely diverging paths. Most of those that are formed close to or within the accel grid are attracted to it and are responsible for the sputtering damage seen during long duration tests.

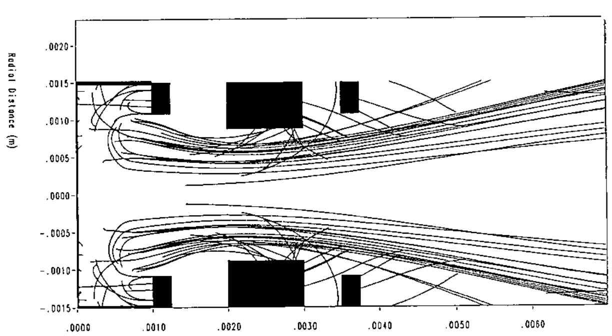

Figure 16 – Computed charge-exchange ion trajectories within the grids for $n_e = 3.5 \times 10^{11}$ cm^{-3}.

Charge-Exchange Ions - Analysis

The production rate, P_c, of relevant charge-exchange ions is given by

$$P_c = n_o n_i \sigma_c v_i A_h d$$

where n_o is the neutral number density within the grids, n_i is the ion number density in the beamlet, σ_c is the charge-exchange cross section at the ion velocity v_i, A_h is the cross sectional area of a single grid hole and d is the approximate distance between the screen and accel grids. Since several of these parameters are constant if the beam accelerating potential is not changed and

$$n_i \propto I_B \propto T \qquad \text{and} \qquad n_o \propto m_d(1-\eta_m)$$

where I_B is the beam current, T is the thrust, m_d is the total propellant flow rate to the discharge chamber of the thruster and η_m is the propellant utilisation efficiency,

$$P_c \propto m_d(1-\eta_m)Td$$

The parameter d remains because the SAPPHIRE software has shown that the sheath penetrates deeper into the discharge chamber plasma as the beam current reduces, thus increasing the volume in which charge-exchange can occur.

To examine the effect that this relationship might have on the relative shape of the beam requires a comparison with the total ion flow rate, N_i, of the normal directed beam current. Since $N_I \propto I_B \propto T$, we have

$$\frac{P_c}{N_i} \propto m_d(1-\eta_m)d$$

As the utilisation efficiency for any thruster falls rapidly with thrust, this in itself provides some explanation of the observed effect. However, this is amplified very considerably by the movement of the plasma sheath; SAPPHIRE modelling results suggest a movement of about 0.5 mm for a change in current or thrust by the factor of 3.5 illustrated in Figures 14 and 15. This is approximately 25% of the screen grid hole diameter.

It is possible to estimate visually the position of the sheath edge in ion distribution plots, such as those shown in Figures 14 and 15. Although imprecise, this process provides an indication of how rapidly the sheath moves into the discharge chamber plasma. The results of such estimates are plotted as a function of n_e

in Figure 17, from which it can be seen that the sheath penetrates rapidly with fall of density, but that this rate decreases as the distance approaches 1 mm. It should be noted that this visual estimate does not necessarily include the pre-sheath region, in which an electric field is set up to accelerate the ions towards the sheath [14].

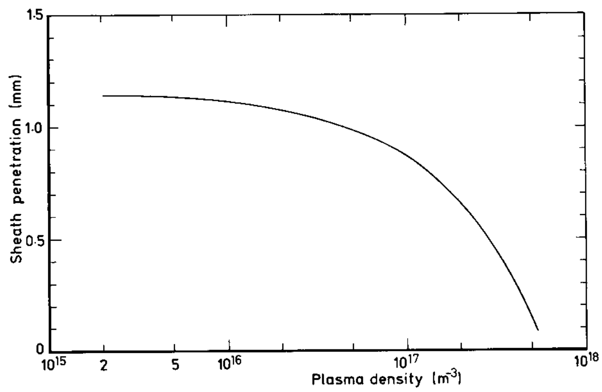

Figure 17 – Sheath penetration into the discharge chamber plasma as a function of n_e.

Spacecraft Implications

Although the values of divergence given by the lower curves in Figure 13 at moderate to high thrust are reasonably consistent with those quoted in the literature for other gridded thrusters [15,16], the implications of the analytical methods used in arriving at these data must not be overlooked. As shown above, the approximations involved in the Gaussian fitting procedure lead automatically to a serious underestimate in the flux of ions at high angles to the thruster axis. These errors become greater as thrust density is reduced.

It should be pointed out that the existence of these ions is intrinsic to the operation of a gridded ion thruster. They cannot be avoided, and their relative effects are accentuated at low thrust. It is therefore essential that their flux be fully documented out to wide angles so that the sputtering effects on spacecraft surfaces at those angles can be properly evaluated. Only very sensitive instrumentation, such as that at the Aerospace Corporation, is fully effective in this region.

Having said that, a typical ion flux is very low indeed and most surfaces would not be adversely effected by it. For example, the results of assessments concerned with the possible erosion of solar arrays on communications spacecraft, due to the efflux from the T5 thruster, have shown that there is no problem, even for north-south station-keeping missions lasting 20 years. However, it would be prudent to make such a detailed assessment for any other host spacecraft, if sensitive surfaces are thought to be at risk.

Conclusions

Several sets of measurements of the ion beam divergence of the T5 thruster have shown the existence of significant discrepancies between the data acquired using different Faraday cup probes. The less sensitive probe designs have provided divergence values less than derived from instruments of much greater sensitivity, and the difference between these values has increased with decreasing thrust, over the range 0.3 to 25 mN. Discrepancies have also been noted between the data obtained using the most sensitive probe and published values for other thrusters with similar grid designs.

It has been established that these effects are due to the current measurement precision of the probe employed and to the techniques utilised for data analysis. In the case of the T5 thruster, the most sensitive ion probe system utilised was that at Aerospace Corporation, which has a sensitivity of around 7×10^{-4} mA/m^2, which is several orders of magnitude better than the other instruments used. In addition, data were taken out to angles of up to 66 deg to the axis of the thruster. It was thus ensured that the peripheral high energy ions were detected and were taken into account during the beam divergence assessment. It should be noted that these peripheral ions are generated in much larger relative numbers at low thrust, enhancing this effect.

With diagnostics of a lower performance, and scanning over a more restricted range of angles, these ions are not usually detected and, as a result, a fit of the beam profile to a Gaussian distribution is normally taken to provide a good measure of beam divergence. This process ignores the peripheral charge-exchange ions, which need to be considered in assessing thruster-spacecraft interactions.

These ions result mainly from the relatively greater production of charge-exchange ions at low thrust, accentuated by the fall in utilisation efficiency as thrust is reduced and by the simultaneous movement of the plasma sheath at the screen grid into the discharge chamber. The latter, together with the trajectories of the charge-exchange ions, have been modelled successfully using the SAPPHIRE Code. These charge-exchange ions are accelerated out of the grid system with the main beam ions, but often at wide angles owing to the locations at which they are produced. They cannot be avoided and are intrinsic to all grid systems on all ion thrusters.

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