Factors Affecting the Beam Divergence of a T5 Ion Engine

by

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Abstract

The aim of this paper is to examine the effects of varying certain operating parameters on the beam divergence of a T5 ion engine fitted with a flight standard grid set. The thruster was tested at the Aerospace Corporation, utilising their well proven Faraday cup probe for beam analysis. Most of the data used for this examination were originally taken to improve knowledge of how the engine operates around the ARTEMIS operating point. It was found that beam divergence increased with reduced propellant mass utilisation efficiency and reduced with increased magnitude of accel. voltage. Inclusion of some previous work indicated that the difference between the screen grid potential and the accel. grid potential (the initial ion accelerating potential) affects divergence rather than solely the accel. grid potential.

Introduction

Ideally, the ion beam from an ion thruster would be perfectly collimated, allowing spacecraft components to be placed within 50mm of the ion beam axis in the case of a T5 thruster. Ions in a fully collimated beam would contribute all of their momentum to producing thrust in the desired direction (i.e. no cosine losses). Unfortunately, the ion beam is not collimated but divergent, restricting the placement of spacecraft components and wasting some of the ion beam energy in the radial direction. The greater the beam divergence the greater the thrust cosine loss and the further away from the thrust centreline that spacecraft components must be mounted.

The investigation reported in this paper used Aerospace Corporation's well proven Faraday cup probe mounted on a rotation table to measure the current density of the emergent ion beam from the T5 thruster under test at a variety of operating conditions. From these data numerical relationships between ion flux density and angular displacement to the thrust vector were developed, along with divergence calculations and thrust correction factors. Calculation of divergence and thrust correction factors \((\alpha_{\text{DIV}})\) assumed that the ion beam is azimuthally symmetric; this has been demonstrated in earlier work in the UK.

Method

The ion thruster used in this work was an engineering model T5 MkIV, fitted with a flight standard 'optimised' grid-set (see Fig.1). It was mounted in a large cryogenically pumped test facility at the Aerospace Corporation. This facility is capable of maintaining a background pressure of \(2 \times 10^{-6}\) torr, corrected for xenon, at the flowrates investigated.

The Faraday cup probe, shown in Fig. 2, is sensitive only to the high velocity ions in the beam. At the probe entrance the ions pass through an electron-excluding stainless steel mesh, then through a 1mm
diameter collimating aperture, then through a 25mm long region subject to a deflecting field of 90V/cm, and finally into a collecting cup biased at 9V to repel low velocity ions and to prevent the escape of secondary electrons. The resultant current is measured by a digital picocammeter that is under computer control via GPIB.

The probe sits on an arm 1.18m long, which is rotated about a vertical axis situated below the centreline of the ion thruster grid-set. This ensures that the Faraday cup probe is always pointed towards the centre of the ion thruster grid system, as shown in Fig.3. Rotation of the Faraday cup probe assembly is carried out under the control of the same computer that stores the picocammeter data. For these experiments, the angular position of the probe with respect to the mechanical axis of the ion thruster was varied between -37° and +66° in 1° increments. At each position the computer stores the picocammeter reading and the angular displacement. When the run has been completed these data are written to a file named by the operator and formatted as an ASCII text file. With this range of angles, the probe samples both the well collimated primary beam and any wide-angle, anomalous ions due, for example, to the charge-exchange process between the grids.

<table>
<thead>
<tr>
<th>Parameter Name</th>
<th>Nominal Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Current ($I_B$)</td>
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</tr>
<tr>
<td>Beam Voltage ($V_B$)</td>
<td>1175V</td>
</tr>
<tr>
<td>Anode Current ($I_A$)</td>
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<td>Anode Voltage ($V_A$)</td>
<td>42V</td>
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<td>Magnet Current ($I_{MAG}$)</td>
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<td>Magnet Voltage ($V_{MAG}$)</td>
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<tr>
<td>Cathode Keeper Current ($I_{CK}$)</td>
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<tr>
<td>Cathode Keeper Voltage ($V_{CK}$)</td>
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<td>Neutraliser Keeper Current ($I_{NK}$)</td>
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<td>Accel. Grid Current ($I_{ACC}$)</td>
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<td>Accel. Grid Voltage ($V_{ACC}$)</td>
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<tr>
<td>Decel. Grid Current ($I_{DEC}$)</td>
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<tr>
<td>Decel. Grid Voltage ($V_{DEC}$)</td>
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<td>Main Flowrate ($\dot{m}_j$)</td>
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<td>Cathode Flowrate ($\dot{m}_c$)</td>
<td>0.090mg/s</td>
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<tr>
<td>Neutraliser Flowrate ($\dot{m}_n$)</td>
<td>0.040mg/s</td>
</tr>
<tr>
<td>Thrust</td>
<td>18mN</td>
</tr>
<tr>
<td>Specific Impulse</td>
<td>3300s</td>
</tr>
<tr>
<td>Propellant Mass Utilisation Efficiency ($\eta_{m}$)</td>
<td>84%</td>
</tr>
</tbody>
</table>

Table I

Nominal uncorrected 18mN operating point for ARTEMIS

The 18mN operating point selected for the ARTEMIS spacecraft was used as the baseline for all the other operating points under investigation. Table I details the ARTEMIS operating point. Note that the mass flowrates were kept constant at all operating points investigated. In all, ten mass utilisation efficiencies ($\eta_{m}$) were selected, ranging from 72% to 90% and six different accel. voltages were chosen (-115V, -150V, -200V, -250V, -300V, -400V), giving a total of 60 different operating points. The main reason for varying the accel. voltage was to determine whether the grid-set was experiencing direct impingement at the ARTEMIS operating point and at what accel. grid voltage electron back-streaming was occurring.

Previously, data were taken with the same ion engine and optimised grid set at a lower beam potential of 1100V and an accel. grid voltage of -225V. Comparison of these earlier data with the main data will show the effects, to a limited degree, of changing the beam voltage on beam divergence and $\alpha_{div}$.

Conversion of the ASCII text files into angular ion density distributions, beam divergences and values of
\( \alpha_{\text{div}} \) were carried out after the data had been gathered using standard mathematical procedures which integrate over the whole beam as explained in the following paragraphs.

At \( 0^\circ \), the Faraday cup probe is looking down the mechanical axis of the ion thruster and, in theory, is subjected to the maximum ion flux density. However, by reference to Figs. 4 and 5, it can be seen that the data maximum occurs at approximately \(-0.5^\circ\) in each case. This is the difference between the mechanical axis of the probe system and the thrust vector, caused by misalignment of the thruster axis with the \( 0^\circ \) position of the rotation table and mismatch of the thrust mechanical axis with the thrust vector. It is important that this offset angle be properly evaluated for each data set as it does have an effect on the calculated beam divergence and \( \alpha_{\text{div}} \).

Previous work\(^2\) has determined that the ion beam is azimuthally symmetric about the mean thrust vector. Using this information, it is possible to calculate the ion beam current passing through an annular element at any angle (up to \( 66^\circ \)) to the ion thruster axis; note that for the purpose of explanation the thrust vector and mechanical axis are assumed to be coincident. This gives rise to the following equations:

\[
J_0 = \frac{4i_0}{\pi d^2 t_f} \quad \text{(E1)}
\]

where:
- \( J_0 \) current density at an angle \( \theta \) to the thruster axis.
- \( i_0 \) current measured by the probe at angle \( \theta \).
- \( d \) diameter of Faraday cup probe aperture.
- \( t_f \) transmission factor

\[
I_\theta = 2\pi R^2 \delta \theta J_0 \sin \theta \quad \text{(E2)}
\]

where:
- \( I_\theta \) current passing through annular element of radius \( R \sin \theta \).
- \( R \) distance from front of Faraday cup probe to centre of decel. grid.
- \( \delta \theta \) angular resolution of probe data.
- \( \theta \) angle between the Faraday cup probe axis and the axis of the thruster.

For calculation purposes all angles are measured in radians.

Summing the current through all the annular elements from \( 0^\circ \) to \( 66^\circ \) gives the total current exhausted by the beam. This is valid because the contribution to the total current from the high angles is virtually zero. Note that the summed current is generally 10% lower than the beam supply current; this is primarily due to charge-exchange interactions downstream of the grids\(^6\).

\[
I_{\text{TOT}} = \sum_{\theta=0^\circ}^{\theta=66^\circ} I_\theta \quad \text{(E3)}
\]

A more general form of the above equation could be written as:

\[
I_\alpha = \sum_{\theta=0^\circ}^{\theta=\alpha} I_\theta \quad \text{(E4)}
\]

where \( I_\alpha \) is the total beam current included by a cone of half-angle \( \alpha \) whose axis is coincident with the thruster mechanical axis.

Combination of E3 and E4 leads to the following equation:

\[
0.95 \times I_{\text{TOT}} = \sum_{\theta=0^\circ}^{\theta=66^\circ} I_\theta \quad \text{(E5)}
\]

which can be solved for \( \theta_{\text{div}} \), the half-cone angle including 95% of the total measured high energy ion current.

A divergent ion beam yields less thrust than would be expected if all the beam current flowed parallel to the thrust centreline. The correction factor is calculated by summing the net axial current \( (i_\theta \cos \theta) \) over the measured angular distribution and dividing by the total current \( I_{\text{TOT}} \):

\[
\alpha_{\text{div}} = \frac{1}{I_{\text{TOT}}} \sum_{\theta=0^\circ}^{\theta=66^\circ} I_\theta \times \cos \theta \quad \text{(E6)}
\]

The thrust correction factor, \( \alpha_{\text{div}} \), can be included in the equation used to calculate thrust from the beam voltage and beam current, along with the thrust correction factor due to the presence of doubly and triply-charged xenon ions \((\alpha_{\text{ion}})\)\(^1\) as shown in equation E7.
\[ F = \alpha_{\text{ion}} \alpha_{\text{div}} I_B \times \sqrt{\frac{2 V_B M_{\text{ion}}}{e}} \]  

where: 
- \( M_{\text{ion}} \) mass of a xenon ion.  
- \( V_B \) ion accelerating potential (beam voltage).  
- \( e \) charge on an electron.  
- \( \alpha_{\text{ion}} \) thrust correction due to the presence of multi-charged ions.  
- \( \alpha_{\text{div}} \) thrust correction due to beam divergence.

**Results**

Fig. 4 shows a plot of ion current density vs angular displacement for an accel. grid voltage of -250V and \( \eta_{\text{m}} \) of 86%. This is typical of the other 59 data sets recorded, there being little difference between them to the 'naked eye'. Fig. 5 shows the same data plotted with a log scale. The characteristic three level pattern has been observed in all data taken previously with the Faraday cup probe. Between angular displacements of +15° and -15° the data can be fitted to a standard distribution equation. Calculating the beam divergence from these fit equations would lead to lower values than those derived from the raw data (as calculated using the equations shown in the previous section). This is because the least squares process of fitting a standard distribution to the data ignores the small currents at higher angles.

In both Figs. 4 and 5 note how symmetrical the data are about the maximum value. This symmetry is consistent throughout the data sets and, together with previous work, lends weight to the necessary assumption that the beam is azimuthally symmetric.

The current density vs angular displacement data for each of the 50 operating points investigated were converted into values for beam divergence and \( \alpha_{\text{div}} \). From these, graphical relationships between \( \eta_{\text{m}} \) and beam divergence, \( \eta_{\text{m}} \) and \( \alpha_{\text{div}} \), accel. voltage and beam divergence and accel. voltage and \( \alpha_{\text{div}} \) may be shown. Rather than showing all thirty possible data sets, those taken at a fixed accel. voltage of -250V and those taken at a fixed \( \eta_{\text{m}} \) of 84% are shown in Figs. 6 to 9. Increasing the magnitude of the accel. grid voltage leads to an increase in beam divergence and a reduction in \( \alpha_{\text{div}} \), while increasing the mass utilisation efficiency leads to a reduction in beam divergence and an increase in \( \alpha_{\text{div}} \).
Table 2
Comparisons of $\alpha_{\text{div}}$ and Beam Divergence for Different Accel. and Beam Voltages

<table>
<thead>
<tr>
<th>$V_B$</th>
<th>$V_{\text{acc}}$</th>
<th>$\eta_m$</th>
<th>Divergence</th>
<th>$\alpha_{\text{div}}$</th>
<th>$V_B - V_{\text{acc}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1175V</td>
<td>-250V</td>
<td>86%</td>
<td>15.3°</td>
<td>0.988</td>
<td>1425V</td>
</tr>
<tr>
<td>1175V</td>
<td>-200V</td>
<td>86%</td>
<td>13.4°</td>
<td>0.989</td>
<td>1375V</td>
</tr>
<tr>
<td>1100V</td>
<td>-225V</td>
<td>87%</td>
<td>12.1°</td>
<td>0.989</td>
<td>1325V</td>
</tr>
<tr>
<td>1100V</td>
<td>-225V</td>
<td>83%</td>
<td>13.2°</td>
<td>0.989</td>
<td>1325V</td>
</tr>
<tr>
<td>1175V</td>
<td>-115V</td>
<td>86%</td>
<td>11.3°</td>
<td>0.991</td>
<td>1290V</td>
</tr>
<tr>
<td>1175V</td>
<td>-115V</td>
<td>82%</td>
<td>12.0°</td>
<td>0.991</td>
<td>1290V</td>
</tr>
</tbody>
</table>

The values shown here for divergence are greater than those generated by earlier work (although values for $\alpha_{\text{div}}$ are approximately the same). Table 2 details the beam divergence and $\alpha_{\text{div}}$ for six operating points. Data contained in the two rows highlighted in bold were taken on a previous occasion and, as observed during the later work, the divergence increases with reduced $\eta_m$. The emphasis of this previous work was to ascertain the beam divergence stability over time rather than to determine the causes of divergence, hence only two operating points were investigated at 18mN.

To summarise this section, the work reported on shows that the beam divergence increases both with a reduction in $\eta_m$ and an increase in the magnitude of the accel. voltage (for a fixed beam potential). Incorporation of the previous work carried out on the same thruster, fitted with the same grid set and using the same Faraday cup probe, indicates that it is the differential voltage between screen grid and accel. grid ($V_B - V_{\text{acc}}$) which affects the divergence rather than purely the accel. grid voltage. At the nominal ARTEMIS operating point, a beam divergence of 16° and $\alpha_{\text{div}}$ of 0.988 were measured.

Discussion of Results

It was seen for all values of accel. voltage used that the divergence increased as the propellant mass utilisation efficiency reduced. This would imply that the increased neutral density in the vicinity of the grid set is affecting the trajectories of beam ions, which is a surprising result, as the mean path for ion-atom collisions in this region is relatively long.

A possible explanation for the dependence of divergence on neutral density is as follows. The sum density of neutrals and ions in the discharge chamber should be independent of $\eta_m$, as long as the flowrates remain constant. Furthermore, the thermal energy distribution of ions and atoms should be similar. As the atoms and ions move around the discharge chamber they impact the internal surfaces, heating them up. However, the electric field between screen grid and accel. grid extends a little way into the discharge chamber, extracting ions that move towards the screen grid before they strike, leaving neutral particles to impact the screen grid, heating it up. Therefore, as $\eta_m$ drops, the rate of neutral impacts...
increases, leading to a hotter screen grid. As the screen grid heats up it expands increasing the gap between itself and the accel. grid. As the degree of separation is non-uniform over the grid, the shape of the extracting electric field is changed as well as the field strength. This may then lead to a change in the beam divergence. While this is a possible explanation, it seems unlikely to be able to account for the large beam divergence changes seen in going from 72% to 90% $\eta_m$.

Another explanation can be given, based on previous work which speculated that as the ion density in the discharge chamber increases, the shape of the plasma sheath formed around each hole of the screen grid flattens. This in turn affects the shape of the accelerating electric field, leading to a reduction in beamlet divergence, and hence a reduction in overall beam divergence.

For a fixed $\eta_m$ the divergence is seen to increase with an increase in magnitude of accel. voltage (Fig.8). However, as put forward in the previous section, it may not be the accel. voltage which determines the divergence but the initial accelerating potential between the screen grid and the accel. grid (i.e. $V_{BR} - V_{ACC}$).

The ions accelerated between the screen grid and the accel. grid are confined by the electric field which keeps them away from the edges of the screen and accel. grid holes. As the electric field strength is increased, by either increasing the beam potential or the magnitude of the accel. voltage, the ions are held in closer proximity to each other as they pass between the grids. This focusing effect is opposed by the mutual repulsion of the ions. When the ions leave the confining influence of the initial accelerating electric field, positive space charge expansion occurs, leading to individual beamlet divergence. The closer the ions are held to each other by the initial electric field the greater the repulsive force between ions and hence the greater the beamlet divergence. The individual beamlet divergences contribute to the divergence measured by the Faraday cup probe.

The ions exiting the plane of the accel. grid are decelerated by the electric field coupling the negative accel. grid and the ambient plasma. If this field is perpendicular to the exit plane of the individual beamlets, then retardation will only take place in the axial direction, and any radial velocity component will be unaffected. This would be manifested as an increase in the beamlet divergence and hence thruster beam divergence as the magnitude of the accel. voltage is increased. This effect would be complicated by the decel. grid, besides which the shape of the external electric field is not known. Varying the accel. voltage and varying the beam voltage to keep the differential potential constant would have allowed investigation of the contribution made to beam divergence solely by the accel. potential. However, as such an investigation was not carried out, this effect will have to be verified by further experimentation.

An investigation into the effects of varying the beam voltage and accel. voltage of an old engineering model triple grid T5 ion engine was carried out subsequent to the work reported on in this paper. Although the same thruster was used in the same facility, an old engineering model grid set was fitted and the method used to measure ion flux was different. Rather than use the Faraday cup probe, a long wire probe was used to measure the line integrated current profile at different axial distances from the ion engine. The results of this work differ from the results generated using the Faraday cup probe in that divergence values are significantly lower and some of the trends are not in agreement. One explanation is that the engineering model grid set behaves in a markedly different way to the virtually undamaged optimised flight standard grid set due to the accel. grid hole erosion of the engineering model grid set and the variation in accel. grid hole diameters of the optimised grid-set.

Perhaps a better explanation lies with the difference between the methods used to calculate values of beam divergence and $\alpha_{pin}$. A least squares fit of a Gaussian function fitted to the data used in this report would give beam divergence values very much in line with the long wire probe results and earlier results.

The difference in the divergence trends may be due to the fact that the long wire probe data were taken at between 5cm and 50cm from the ion engine while the Faraday cup probe was situated 118cm from the engine.

**Conclusions**

This work shows that there is a definite correlation between accel. grid potential (at a fixed beam potential) and beam divergence. As there were not enough data available at different beam potentials it cannot be stated with absolute certainty that this
correlation is a subset of a more general trend between the initial accelerating potential \( V_{BE} - V_{ACC} \) and beam divergence. However, if the appropriate experiments were carried out using the Faraday cup probe and a T5 ion engine fitted with an optimised grid set then such a trend would be expected.

A strong correlation between propellant mass utilisation efficiency and beam divergence was measured. While the screen grid may indeed get hotter at lower values of \( \tau_{ion} \) thereby expanding and changing the electric field between screen grid and accel. grid, it seems unlikely that this alone can account for the large observed changes in beam divergence. However, no other explanation is at present available.

As the beam divergence is reduced with a reduction in accel. grid voltage magnitude, it would seem beneficial to run the thruster with as low an accel. voltage as possible. This has the further benefit of reducing the impact energy of charge exchange ions striking the accel. grid, leading to an improved grid set life. While the ion thruster, using a new grid-set is capable of running with an accel. grid voltage of as little as -115V it does not necessarily mean that the grid-set is capable of operating at this voltage when it is at the end of its life. What is required is some further tests using a grid-set machined to imitate the conditions at end of life. This may lead to the conclusion that it would be beneficial to vary the accel. grid voltage over the life of the thruster.

In none of the operating point chosen did the thrust correction coefficient drop below 0.98 which is equivalent to a loss of 0.36mN at 18mN. This slight reduction in desired thrust can easily be compensated for, along with the effects of doubly-charged ions. Quantifying the operational effects of gross beam divergence and, more importantly, the angular distribution of ion flux density over the complete exit plane of the thruster is more difficult, as they depend on the spacecraft configuration.

**Acknowledgements**

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**References**