Direct Thrust Measurements and Beam Diagnostics on an 18-cm Kaufman Ion Thruster

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With a particular thrust dynamometer suspended by critically loaded columns direct thrust measurements on the mercury electron bombardment ion thruster ESKA 18-P have been carried out. The results confirm experimentally that the effective thrust is about 10% lower than the nominal thrust calculated from the electrical data. No influence on the thrust deviation due to a relative change of the absolute double ion content at different discharge voltages and constant beam current could be recognized. However, the thrust deviation showed a dependence upon the positive high voltage at fixed negative high voltage. This seems to be connected with the influence of beam divergence and is compatible with qualitative measurements of beam current density profiles. In search of further possible thrust loss mechanisms, a hypothetical ion leakage to the neutralizer was investigated by probing the near-grid region of the beam with a multiple Langmuir probe. Although a remarkable distortion of the ion density and the floating potential distributions at the neutralizer position was observed its thrust reducing effect seems to be low.

Nomenclature

F_E = effective thrust, mn
F_N = nominal thrust, mn
ΔF = absolute thrust deviation $F_N - F_E$, mn
f = relative thrust deviation $\Delta F/F_E$, %
$\bar{f}$ = mean relative thrust deviation, %
f_Φ = relative thrust deviation due to beam divergence, %
I_+ = ion beam current, ma
I_D = discharge current, a
j_+ = ion current density, ma/cm^2
j_e = electron current density, ma/cm^2
$\dot{m}_p$ = propellant mass flow rate (without neutralizer mass flow rate), ma current equivalent
q = electrical charge, as
U_+ = positive high voltage, kv
U_- = negative high voltage, kv
U_D = discharge voltage, v
U_N = neutralizer potential, v
U_s = probe potential, v
w_i = specific ionization energy, ev/Ion
η_m = propellant mass utilization coefficient (without neutralizer), %
μ = ion mass, kg
Φ = beam divergence angle (angle between beam axis and beam edge)

Introduction

THE nominal thrust calculated from the electrical performance data of an electrostatic ion thruster gives the ideal value for the thrust only:

$$F_N = (2\mu/q)^{1/2} I_+ \, U_+^{1/2}$$

In practice, there exist a number of nonideal effects which can reduce the effective thrust; a) electrode grid misalignments, b) doubly charged ions, c) beam divergence, and d) neutralizer influence. With respect to possible thrust reducing mechanisms, direct measurements of the effective thrust seem to be important for the evaluation of ion thruster performance. This was the motivation for the development of a suitable thrust measuring device and the realization of direct thrust measurements on the electron bombardment ion thruster ESKA 18-P of DFVLR Braunschweig.

In order to get more knowledge about the basic thrust loss mechanisms and the influence of the neutralizer on the beam, supplementary measurements with single and multiple Langmuir probes in the beam have been performed. While the single probe could be used only for measurements on one radius, the loci of measurement of the multiple probe lay on nine radii across the beam. The multiple probe was suitable especially to survey the beam region between accelerator grid and neutralizer, as well as the beam region further downstream.

Experimental Setup

Thruster

The thruster used for the experiments is the 18-cm-diam mercury electron bombardment ion thruster ESKA 18-P which is described in Ref. 1. The molybdenum screen and accelerator grids were identical: 1 mm thick, 4 mm hole diam, 75% open area, 1.5 mm gap between the grids. The range of performance of the ESKA 18-P engine is given by the field of characteristic lines, Fig. 1, which is valid for the thruster with 9 permanent bar magnets at a mass flow rate ratio of 1 : 8.3 (cathode to main flow rate) and a positive high voltage of $U_+ = 1.5$ kv. The negative high voltage is $U_- = -1.0$ kv; it was kept fixed at this value during the entire experiments. Of course, fields of characteristic lines differ for different high voltages.

The point of operation for the thrust measurements and the multiple Langmuir probe measurements is indicated by point A in Fig. 1 at a constant ion beam current of $I_+ = 400$ ma. This ion beam current was kept constant over the whole high voltage range ($U_+ = 0.8 \ldots 2.2$ kv) by varying the mass flow rate. For

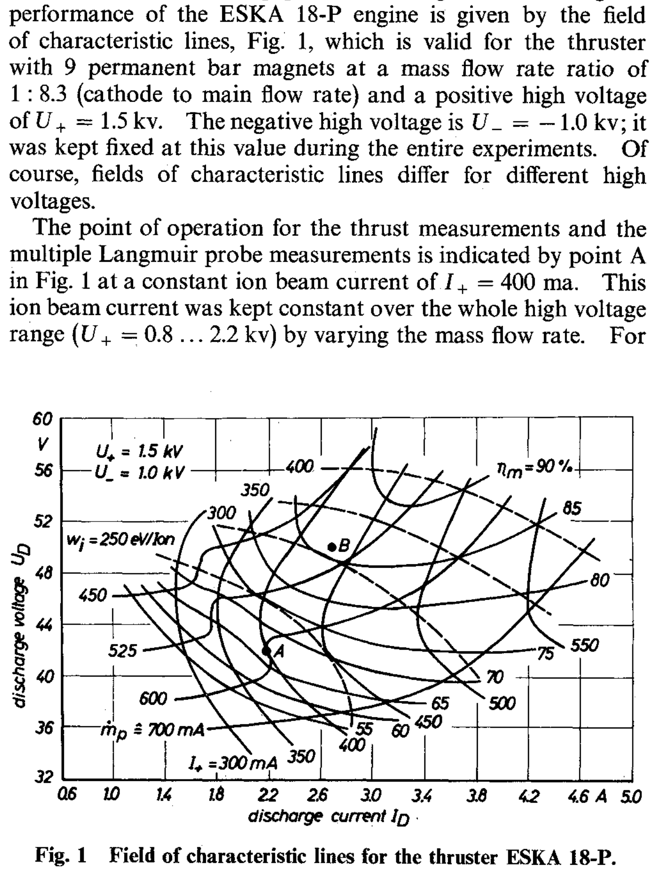

Fig. 1 Field of characteristic lines for the thruster ESKA 18-P.

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the thrust measurements at extreme high discharge voltages the diagram in Fig. 1 is not representative because of the lower mass flow rates. The ion current density measurements with the single Langmuir probe for determination of the beam divergence were performed at nonfixed ion beam currents between 330 ma and 380 ma. All experiments were made in a 5 m long, 2 m diam test facility at a vacuum pressure in the region of 10^{-5} torr. The nominal operating point for a supposed near earth application of the thruster ESKA 18-P is point B in Fig. 1.

Thrust Measuring Device

The thrust dynamometer works on the well known Hansen principle which uses critically loaded columns as suspension and a thrust compensating feedback circuit as force sensor.[2-4] Figure 2 shows a schematic of the thrust measuring system. A displacement of the thruster generated by the thrust is measured by means of an inductive displacement transducer which is part of a 5 kHz carrier frequency bridge circuit. The demodulated bridge output signal is switched on an integral action regulator which controls the current to a force motor (loudspeaker magnet with moving coil) to reset the displacement. In the state of zero displacement the thrust is equal to the restoring force which is proportional to the force motor current. For calibration of the dynamometer a second identical force motor is used by which known force values can be introduced to the system. The current-force characteristics of the force motors were carefully determined with a highly accurate double pan balance.

For leveling and adjusting, special positioning elements are installed which can be manipulated from outside the vacuum chamber. As the device is very sensitive to temperature gradients it is surrounded by a reflecting aluminum foil as a heat shield. Furthermore, the temperature of the device inside the foil isolation is monitored as zero drift effects can be avoided only if the temperature of the device is constant. Because of damping there are no problems due to vibration. The electrical and mercury leads to the thruster are helically wound, so that due to their high flexibility there are no provable interferences.

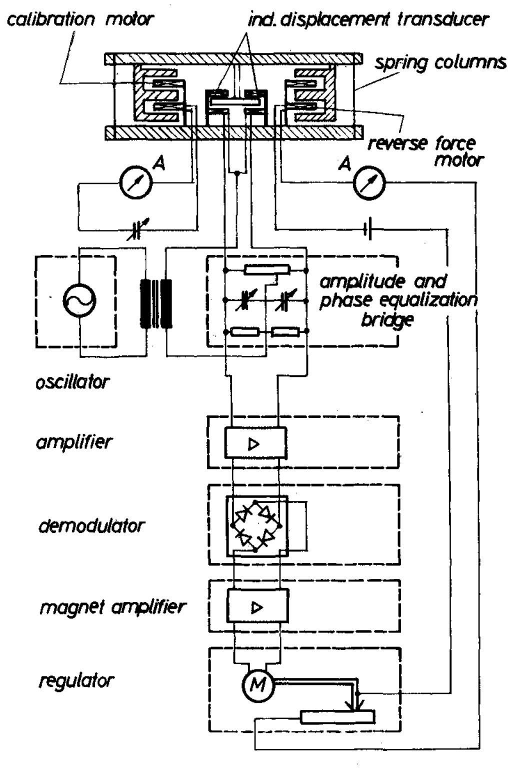

Fig. 2 Schematic of thrust measuring system.

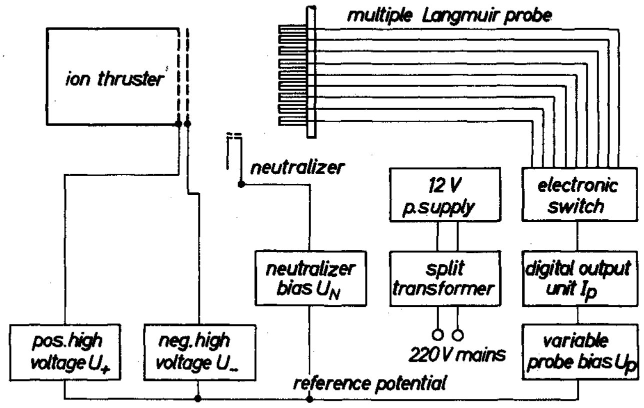

Fig. 3 Schematic of multiple Langmuir probe circuit.

The sensitivity of the thrust measuring device is 0.83 mn per ma of force motor current, the smallest measurable force was determined to 1.7 10^{-2} mn. In the interesting thrust range between 12.5–50 mn the resolution is 0.4 mn and the mean error ± 0.5 mn which is $\pm 1\%$ of the measuring range.

The thrust measurements were carried out by the on-off method: after some minutes of thruster operation the positive high voltage of the thruster was cut off for a moment of no thrust generation and then was switched on again. This procedure made sure that in any case no uncontrolled zero drifts of the thrust readings occured. The mean of the force differences at off-on and on-off, respectively, was taken as the actual measured value of the momentary thrust.

Langmuir Probes

While a movable single Langmuir probe was used for the purpose of beam divergence measurements, a multiple Langmuir probe became useful for probing the beam between accelerator grid and neutralizer. The multiple Langmuir probe consists of a main quartz tube of 16 mm diam as swivel arm with 9 perpendicularly arranged smaller tubes of 5 mm diam and 50 mm length. The length of these single tubes is determined in such a manner that it becomes possible to probe the beam right to the accelerator grid. The actual Langmuir probes are molybdenum disks of 3 mm diam. The swivel arm with the 9 single probes can be rotated to a certain extent dependent on its axial position. The distance from the thruster axis to the swivel axis is 260 mm. The axial position can be varied by steps of 5 mm.

The schematic of the multiple probe is shown in Fig. 3. The single Langmuir probes are connected to an electronic check switch which is followed by a digital output unit which in the μamp-range has an inner voltage drop of 1 mv/μamp. The digital output unit as well as the electronic check switch power supply are separated from the grounded 220 v ac mains by means of a 5 kv-isolating split transformer. The variable probe bias is applied by a 300 v/0.5 amp voltage supply which is related to the reference potential of the thruster.

Results

Thrust Measurements

Neglecting electrode grid misalignments, the double ionization and the beam divergence were supposed as the main thrust reducing effects. To investigate the relative influence of double ionization the thruster was run through its thrust range at the most different discharge voltages which could be realized with a constant ion beam current. From the cross section for electron-atom interactions of mercury as a function of electron energy the current densities of singly and doubly charged ions at different discharge voltages can be derived. The ratio of

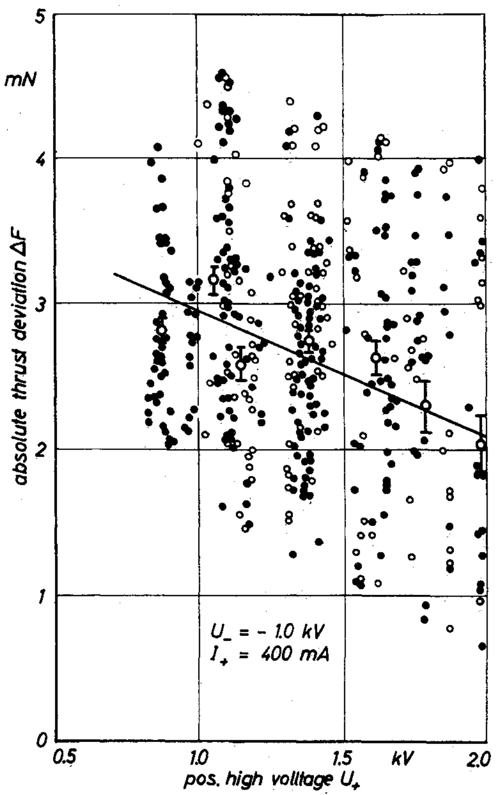

Fig. 4 Measured thrust loss ΔF vs corresponding positive high voltage U_+. The solid points represent low discharge voltages ($U_D = 34 \ldots 44$ v), the open points high discharge voltages ($U_D = 54 \ldots 64$ v).

double to single ion current density at a discharge voltage of $U_D = 60$v is expected to be a factor 10 larger than at $U_D = 35$v. In terms of thrust this means that the difference ΔF between calculated thrust F_N and measured thrust F_E increases from 0.3 mn at $U_D = 35$v to 3.0 mn at $U_D = 60$v (at $I_+ = 400$ ma, $U_+ = 1.5$ kv, and $U_- = -1.0$ kv). The relative thrust deviation f can be expected to differ by 5.32% between the two discharge voltages. Thus, by theory a growing influence of double ionization on the effective thrust by increasing the discharge voltage at fixed beam current should be measurable.

To determine the influence of beam divergence on the effective thrust the thruster was run through its thrust range by variation of the positive high voltage from 0.8 kv to 2.0 kv at const $U_- = -1.0$ kv and const $I_+ = 400$ ma. From single Langmuir probe measurements the different U_+ values could be attached to a certain amount of beam divergence. The results of these measurements are given in the Probe Measurements section.

The results of the thrust measurements can be seen from Fig. 4 where the difference values ΔF between the calculated nominal and the measured effective thrust are plotted versus the corresponding positive high voltage U_+ of the thruster. The data points from the measurements at low and high discharge voltages are marked. Surprisingly, no clear separation of the two data groups at different discharge voltages can be recognized. From a statistical evaluation of the measured data an average line can be derived which shows a recognizable dependence upon the positive high voltage.

Probe Measurements

Beam Divergence

Beam divergence was determined from ion current density measurements performed with a single Langmuir probe. At axial distances from the accelerator grid of 100, 200 and 300 mm the probe mounted on a swivel arm of 260 mm length

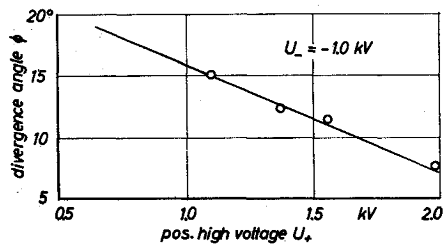

Fig. 5 Dependence of beam divergence angle Φ on the positive high voltage U_+.

(distance between swivel axis and thruster axis) was turned across the beam. By this, current density profiles in the horizontal plane through the beam axis were achieved.[4] The edge of the beam was defined by the 10% values of the current density profiles maxima giving the divergence angle Φ as the angle between beam edge and beam axis. The deflection of the beam axis relative to the thruster axis was about 1° and therefore negligible.

The measurements were carried out at several U_+ values between 1.0 and 2.0 kv while U_- was kept constant at -1.0 kv (I_+ between 330 and 380 ma). This means a range from 0.50 to 0.67 of the ratio $U_+/(U_+ + |U_-|)$. As this ratio here is fixed by the U_+ values alone Fig. 5 shows the dependence of the divergence angle Φ on the positive high voltage U_+. This result which is in good agreement with Ref. 5 can be correlated with Fig. 4 for the evaluation of the beam divergence influence in thrust loss.

Ion Current Density Distribution

The distribution of ion current density in the near thruster region of the beam was investigated with a multiple Langmuir probe. To determine the appropriate bias voltage to the single Langmuir probes for measuring ion currents, several current-voltage characteristics sensed at different locations in the beam have been carried out. As expected, the axial position of the neutralizer was decisive. The typical part of the current-voltage-characteristic for the lower probes 9, 8, 7, and 6 (9 is nearest to the neutralizer) shows that a negative bias voltage of about 10v is necessary to come into the ion saturation region where all electrons are repelled (Fig. 6). In this case the neutralizer voltage was $U_N = -6.5$v with respect to the reference potential. Thus, all ion current density measurements were carried out at a probe bias of $U_s = -10$v.

The axial ion current density distributions for $U_+ = 1.0$ and 1.5 kv ($U_- = -1.0$ kv, $I_+ = 400$ ma) in the vertical plane of the beam are shown in Fig. 7. The positions of the accelerator grid and the neutralizer as well as the distance from the accelerator grid are indicated. The maximum ion current density lies in the order of $j_+ = 3$ ma cm.$^{-2}$ While the upper section of the beam (opposite to the neutralizer) has a rather homogenous current distribution, the lower section of the beam

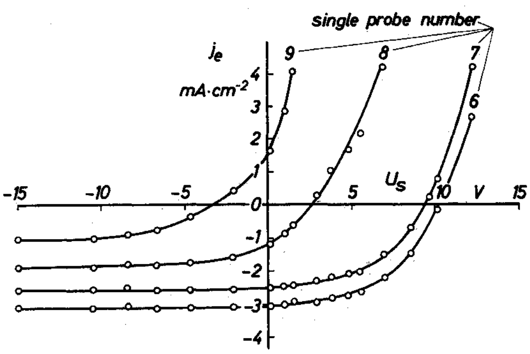

Fig. 6 Current-voltage-characteristics for the four lower probes of the multiple Langmuir probe at the axial position of the neutralizer.

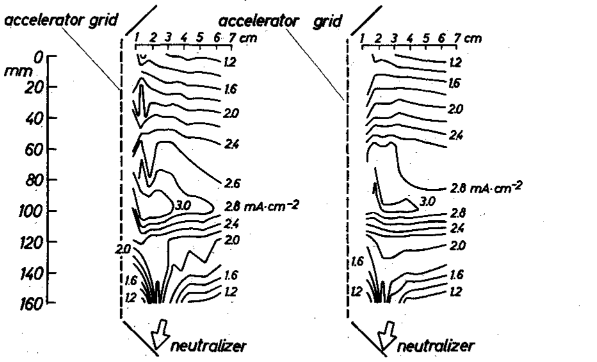

Fig. 7 Axial ion current density distributions for the positive high voltages $U_+ = 1.0$ kv (left) and $U_+ = 1.5$ kv (right) at $U_- = 1.0$ kv, $I_+ = 400$ ma.

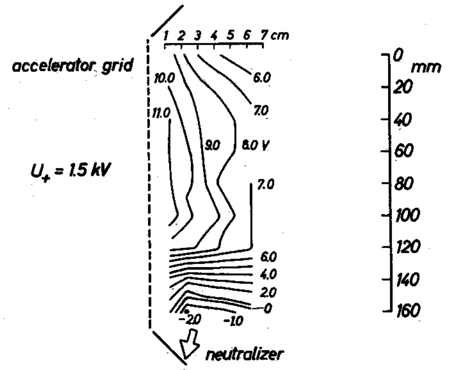

Fig. 10 Axial floating potential distribution at $U_+ = 1.5$ kv, $U_- = -1.0$ kv, $I_+ = 400$ ma (neutralizer potential $U_N = -6.5$ v).

is heavily distorted by the neutralizer. Lines of constant axial ion current density are shaped in the direction towards the neutralizer. As can be seen from these graphs, at low U_+ values lines of higher ion current density are deflected to the neutralizer than at high U_+ values. As a consequence of this effect, the maximum of the ion current density which initially is well in the beam axis is deflected towards the neutralizer. This seems to indicate that the neutralizer draws an ion current which at low U_+ values is higher than at high U_+ values. In addition to the axial cross section of the beam in the vertical plane, Fig. 8 and Fig. 9 give a radial cross section of the axial ion current density distribution at different axial positions, both at $U_+ = 1.5$ kv, $U_- = -1.0$ kv, $I_+ = 400$ ma. The same general result is obtained as before.

Floating Potential Profiles

To get an idea what the potential distribution in the beam looks like, it is obvious to plot the floating potentials from the current-voltage-characteristic of each single probe. As is known, the floating potential is easily determined by the condition that no current is drawn by the Langmuir probe. The result of this procedure is shown in Fig. 10, where again the same plane of the beam is taken as in Fig. 7. Related to all probe measurements it should be pointed out here that secondary effects like electron emission have been neglected.

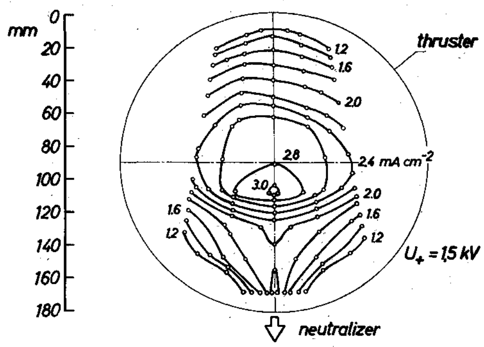

Fig. 8 Radial cross section of axial ion current density distribution at an axial distance from the accelerator grid of 22.5 mm (neutralizer position); $U_+ = 1.5$ kv, $U_- = -1.0$ kv, $I_+ = 400$ ma.

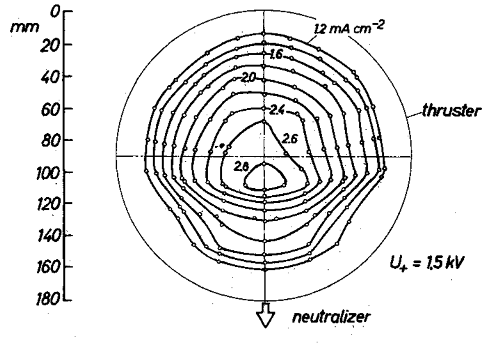

Fig. 9 Radial cross section of axial ion current density distribution at an axial distance from the accelerator grid of 62.5 mm; $U_+ = 1.5$ kv, $U_- = -1.0$ kv, $I_+ = 400$ ma.

Discussion

From Fig. 4 an average thrust loss ΔF between 2 and 3 mn in the present case of the thruster ESKA 18-P can be derived. As no systematic difference between the thrust loss at two highly different discharge states is observed the relative change of double ion content due to discharge voltage variations must be smaller than the simple theory predicts. The theoretical thrust loss difference of nearly 3 mn between $U_D = 35$v and $U_D = 60$v is based on the assumption that within the discharge all electrons have the uniform energy related to the respective discharge voltage. It is evident, however, that the real electron energy distribution departs from this ideal assumption. Although no relative influence of double ionization on the thrust within the operating range of the thruster could be detected this gives no evidence of the absolute double ion content and its important contribution to thrust reduction.

The thrust deviation ΔF and f, respectively, as well as the divergence angle Φ are dependent on the positive high voltage U_+ (at fixed negative high voltage U_-). Looking for a connection between thrust deviation and divergence in Fig. 11 the averaged experimental relative thrust deviation $\bar{f}$ is compared with the theoretical[6] relative thrust deviation f_Φ due to the measured beam divergence which because of Fig. 5 is dependent on U_+ as well. This comparison indicates an only small contribution of beam divergence to the total thrust deviation

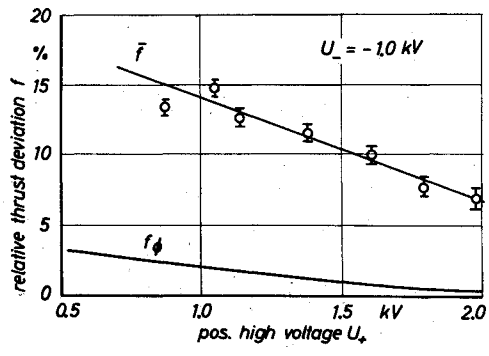

Fig. 11 Averaged experimental relative thrust deviation $\bar{f}$ and theoretical relative thrust deviation f_Φ due to beam divergence vs positive high voltage U_+ ($U_- = -1.0$ kv).

in the region of 10%. However, it should be noted that the evaluation of beam divergence and the thrust deviation f_ϕ, respectively, from the single Langmuir probe measurements gives qualitative results only.

According to the measured ion current density distributions a considerable distortion of the beam uniformity by the neutralizer is observed. The question was whether the phenomenon could influence the thrust. This would happen if ions were attracted by the neutralizer and withdrawn from the thrust generating process, but being included in the ion beam current reading and thus in the calculated thrust. The balance between neutralizer current and ion beam current would not be affected because the loss ions would be included in the reading of neutralizer current.

This hypothetical thrust loss mechanism would hold true only if the measured current distributions could be interpreted as a leakage of beam ions to the neutralizer. However, the beam ions due to the acceleration voltage have a too high kinetic energy as a deflection to the neutralizer appears probable. More probable would be that the distortion of the ion current density distribution is caused by charge exchange ions produced within the neutralizer plasma bridge. Such charge exchange ions easily can be attracted by the neutralizer (as well as by the Langmuir probes themselves which have a low negative potential in the same order of mangitude). But as the ratio of charge exchange ion current to beam current lies in the range of 10^{-3} this means that any thrust loss due to charge exchange effects in the neutralizer region is negligible.

Conclusions

Direct thrust measurements on a specific 18-cm Kaufman ion thruster give evidence that the effective thrust is considerably lower than the nominal thrust derived from the measured electrical data of beam current and positive high voltage. The amount of measured thrust deviation lies between 2 and 3 mn in the present case, that means a relative thrust deviation between 7% and 14%. The thrust loss showed a dependence upon the positive high voltage U_+ (at a const negative high voltage of $U_- = -1.0$ kv). So the lower values above correspond to $U_+ = 2$ kv, and the higher to $U_+ = 1$ kv. From the qualitative beam divergence measurements it is concluded that the decrease of thrust loss with increasing positive high voltage is connected with beam divergence. As the thrust measurements at different discharge voltages did not yield any recognizable change in thrust loss it is suggested that the absolute content of doubly charged ions is a function not only of discharge voltage but also of other physical parameters which characterize the ionization processes. The observed distortion of the ion current distribution in the neutralizer region of the beam is interpreted as a charge exchange influence with negligible contribution to the measured thrust loss.

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