Ion Flow Experiments in a Multipole Discharge Chamber

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It has been customary to assume that ions flow nearly equally in all directions from the ion production region within an electron-bombardment discharge chamber. Ion flow measurements in a multipole discharge chamber have shown that this assumption is not true. In general, the electron current through a magnetic field can alter the electron density, and, hence, the ion density, in such a way that ions tend to be directed away from the region bounded by the magnetic field. When this mechanism is understood, it becomes evident that many past discharge chamber designs have operated with a preferentially directed flow of ions.

Introduction

THE efficiency of an ion thruster used for electric space propulsion is an important parameter. The discharge loss (the power used to generate beam ions) is the major loss involved in this efficiency. A reduction of discharge loss then can be translated directly into an increase in thruster efficiency.

Discharge loss correlations have indicated that, for similar utilization conditions, the volume production cost for ions is roughly constant.[1,2] This means that discharge losses can be reduced by extracting a larger fraction of the ions produced. It has been generally assumed that, for normal operation, ions tend to flow nearly equally in all directions. According to this assumption, the fraction of ions that is extracted into the ion beam is determined by the ratio of the extraction area to the total surface area surrounding the ion production region. The fraction of ions that is extracted therefore can be enhanced by using a discharge chamber with a depth that is small compared to the beam diameter. A reduction in discharge chamber depth, however, can be constrained by a need for high propellant utilization.

The fraction of ions extracted could be increased without compromising the propellant utilization if the discharge chamber walls could be configured so that the ion flow to the walls is reduced. A larger chamber depth could then be used to increase the probability of ionization, without a corresponding increase in ion loss to the walls.

An ion containment mechanism has been proposed in the past, and sufficiently low discharge losses were obtained in some designs to indicate that some form of ion containment might have been obtained.[3,4] However, the mechanism proposed depended on anodes being biased positive of the plasma to "reflect" ions. Further, subsequent experiments have failed to show any significant decrease in discharge losses for a multipole design when the anodes were biased positive relative to the discharge plasma.[5]

A detailed study is presented herein of the effects of various operating parameters on the ion flow within a multipole discharge chamber. Although a multipole chamber is used, many of the results are applicable to more general containment configurations.

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Apparatus and Procedure

The thruster used herein is rectangular in shape and has been described in previous publications.[6,7] The rectangular shape makes the thruster well suited to changes of the anode and magnetic pole-piece configuration. The description herein will be limited to those aspects directly involved in the experiments.

A cross section of the thruster used is shown in Fig. 1. The internal dimensions of the discharge chamber (circumscribed by the screen grid and pole pieces) were 7.5 cm deep, 10 cm wide, and 45 cm long. (The 45-cm dimension is normal to the page in Fig. 1.) There were no pole pieces at the ends of the discharge chamber. The ion-beam extraction area was 5×40 cm, with a 58% open screen grid within this area. The small size of the extraction area, relative to the overall length and width of the chamber, resulted in a large discharge loss per extracted ion. But the distribution of the various losses within the chamber were of more interest in this investigation than the actual magnitudes of the measured discharge losses per extracted ion. The design, although not optimized for efficiency, was well-suited to the types of experiments required.

The magnetic field integrals for the back anodes were tested at mean values from about $70\text{-}240 \times 10^{-6}$ T-m (70-240 G-cm). The side anodes (three on each side in Fig. 1) were operated at mean values from $50\text{-}60 \times 10^{-6}$ T-m in all tests.

Several anode bias arrangements were tested. The arrangement of most interest was with the six side anodes connected directly to the discharge power supply, and the four back anodes operated at various degrees of positive bias relative to the side anodes. Some tests were also conducted with two of the back anodes held at cathode potential so that they were not conducting discharge current.

A variety of probes was used to determine properties of the discharge plasma and ion arrival rates at each class of surfaces within the discharge plasma. Bulk plasma properties were obtained with a Langmuir probe, while a planar probe was used to evaluate Bohm current density within the bulk discharge plasma independently. Because the planar probe provided a direct measurement of Bohm ion current density, it was felt to be more reliable than the value indirectly calculated from the electron temperature and plasma density obtained from Langmuir probe data. Conformal probes, insulated with layers of polyimide, were used to measure ion arrival rates to various surfaces.

The discharge voltage was held constant at 40 V. The propellant was argon, with the flow maintained at 7.0 standard cm^3/min. Due to the backflow from the $\sim 4 \times 10^{-4}$ Torr facility environment, the effective flow was higher. The discharge currents of 1-9 A corresponded to low utilizations up to approximately the "knee" of the discharge loss curve.

Experimental Results

Typical results of anode bias tests are shown in Fig. 2. Measurements of the plasma potential during these tests showed that it was substantially independent of the back anode potential. Thus, for biases greater than 2-5 V, the back anodes were more positive than the plasma potential.

Despite the positive potential of the back anodes, no evidence of "ion reflection" was found. Instead, the discharge loss increased monotonically with bias potential. The amount of this increase could be made smaller by increasing the magnetic integral of the back anodes. At an integral of 241×10^{-6} T-m, the losses for different biases were effectively reduced to a single curve. Although the adverse effects of anode bias were eliminated by the higher magnetic integral, there were still no beneficial effects to be observed from such a bias.

The discharge power during biased operation could be separated into what might be termed "productive" and "biased anode" portions. The productive power was defined as the discharge current times the discharge voltage. The biased anode power was the current to the back (biased) anodes times the bias voltage. Because the plasma potential did not change significantly with bias voltage, this biased anode power must have been dissipated in the magnetic field near the back anodes. Further, studies of the diffusion processes involved indicate that most of the bias potential difference appears close to the anodes involved.[8] The power for biasing the back anodes, therefore, is believed to contribute little to the generation of ions that reach the ion optics.

When the biased anode power was subtracted from the total discharge power, the data of Fig. 2 were reduced to a single line for all bias voltages. Data for other magnetic integrals were also reduced to a single line for all bias voltages by using this technique. This indicates that the major effect of biasing is simply to dissipate additional power near the anodes being biased.

The wide range of magnetic integrals and biases used for the back anodes also provided a systematic investigation of electron diffusion through a multipole magnetic field. A previous study[8] indicated that small electron currents through the magnetic field are accommodated by density gradient diffusion, and larger currents result in the establishment of a potential difference to the low-density end of the density gradient region near the anode. From this study, an effective magnetic integral was defined as

$$(\int B\mathrm{d}x)_{\mathrm{eff}} = \int B\mathrm{d}x - (\int B\mathrm{d}x)_{\mathrm{therm}} - (\int B\mathrm{d}x)_{\Delta V} \qquad (1)$$

where $\int Bdx$ is the total magnetic integral between the anode and the plasma discharge; $(\int Bdx)_{\mathrm{therm}}$ is the field integral to which an electron at the most probable thermal velocity can penetrate (corresponding to two cyclotron radii); and $(\int Bdx)_{\Delta V}$ is the magnetic integral that can be crossed by an initially motionless electron due to a potential difference of ΔV, in this case assumed to be the bias potential. This definition of net magnetic integral is consistent with the assumptions found previously to agree best with experimental measurements of electron diffusion.[8] That is, the electron current should be determined by density gradient diffusion over the net magnetic integral.

The electron diffusion data were correlated using this net magnetic integral, as indicated in Fig. 3. The fraction of the discharge current conducted by the back anodes, J_b/J_d, clearly varied in an inverse manner with the value of the magnetic integral. Another result was the initial rapid increase in anode current with bias voltage, followed by a leveling off, or saturation, at higher values of bias voltage. This saturation would be expected from the diffusion model used. The slow approach to saturation in Fig. 3, however, indicates that there is some blending of the density gradient and potential difference diffusion processes.

To better understand what was happening in the discharge chamber, surface probes were used to evaluate ion flows to various discharge chamber surfaces. A detailed evaluation at pole-piece surfaces gave the results indicated in Fig. 4. The peak ion current density was found on the exposed edges of the pole pieces, with a current density value at this location close to the Bohm value in the bulk of the discharge plasma.

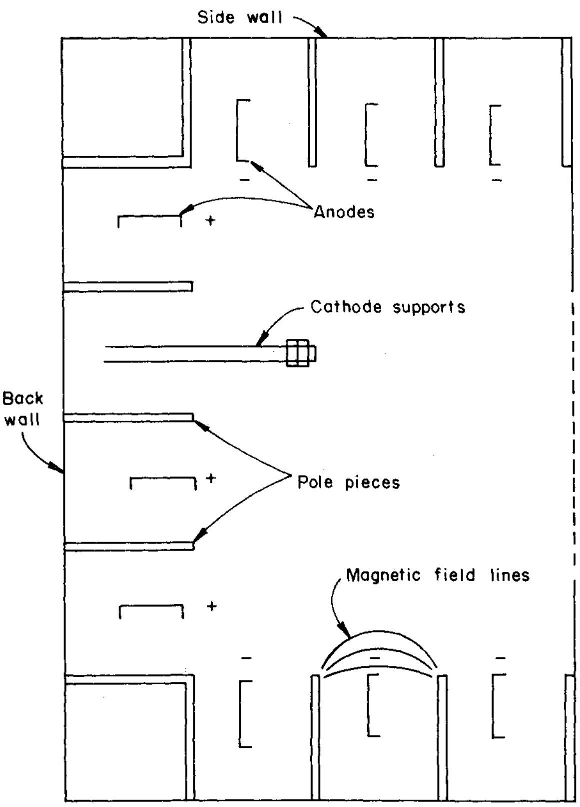

Fig. 1 Discharge chamber cross section.

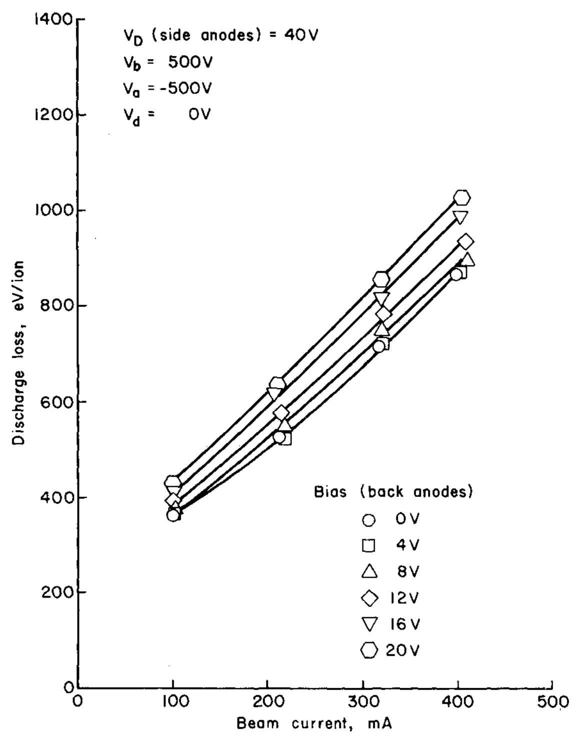

Fig. 2 Discharge loss vs. beam current for a back anode magnetic integral of 118×10^{-6} T-m.

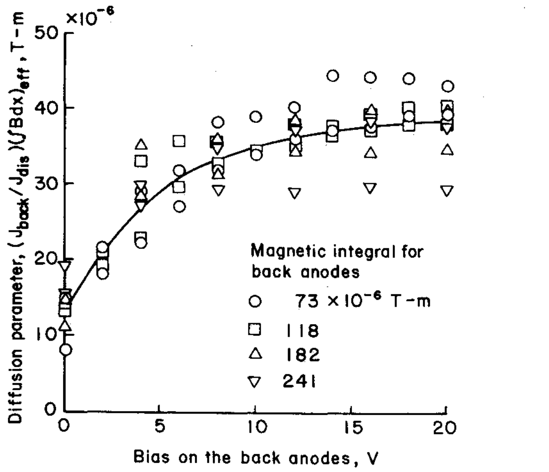

Fig. 3 Correlation of back anode current ratio as a function of bias voltage using the effective magnetic field integral.

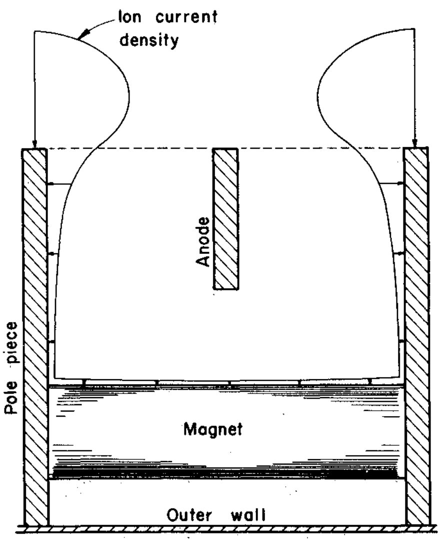

Fig. 4 Ion arrival rate in multipole configuration (length of arrows indicates magnitude of arriving ion current density).

When averaged over the equivalent boundary, indicated by the dashed line in Fig. 4, the ion arrival rate corresponded to only about one-fourth of the Bohm value. This arrival rate was nearly constant (~0.21-0.26) regardless of discharge current or positive anode bias.

The ion arrival at the anode surface was investigated also. To obtain an ion current, the anode probe required a negative bias to near cathode potential. Because the probe covered a section of the anode about 0.5 cm long, this large negative potential may have been a significant disturbance on local ion flow. The measured ion flow, about one-third of that to a pole piece, therefore should be considered the upper limit of the possible ion flow during normal operation.

Using ion flow measurements from a number of probes on different discharge chamber surfaces, it was possible to estimate the total ion production. The total ion production was a function only of discharge current. As mentioned earlier, the propellant flow and discharge current voltage were held constant so that the range of discharge current corresponded to a utilization range up to approximately the "knee" of the discharge loss curve. The volume production cost increased monotonically from about 53 eV/ion at a 1-A discharge to about 77 eV/ion at 9 A.

The extraction efficiency of the ion optics also varied, so that energy per extracted ion varied over a larger ratio. Based on the Bohm current density and the screen open area, the extraction efficiency decreased from about 86% at a 1-A discharge to about 65% at 9 A. The 45% increase in volume ion cost over this discharge current range was thus translated into almost a doubling of loss for extracted ions. It should also be noted that the relatively low maximum value of extraction efficiency, 86%, is believed to be the result of a fairly thick screen grid—0.51 mm compared to a screen-hole diameter of 2.0 mm.

Tests were also conducted with two back anodes held at cathode potential to determine the effect on ion flow. With an anode switched to cathode potential, the ion losses to that anode and the associated pole pieces were about double the ion losses with an operating anode. Most of this increase was due to increased ion arrival at the anode. This large increase in ion loss with an anode set at cathode potential was also the reason for suspecting that a macroscopic probe at cathode potential on an operating anode would give excessively high ion currents.

From the ion arrival rates with both operating and cathode-potential anodes, it is clear that an operating anode directs much of the local ion flow away from that anode. From the anode bias tests, the exact level of electron current to an operating anode appears to be unimportant in determining this preferential ion flow. But effectively stopping the electron current by reducing the anode to cathode potential stopped much of the preferential ion flow.

It should be noted that the ion losses for an anode at cathode potential rose to only about one-half of the Bohm value when averaged over the local boundary area. Only two anodes were switched at a time because the discharge could not be maintained with a greater number of anodes not conducting discharge current. Therefore, it might be hypothesized that the ion flow to an inoperative anode represented a flow compromise with adjacent operating anodes.

Proposed Ion Flow Model

From the preceding experimental results, it should be clear that the preferential flow of ions toward the ion optics can exist as a part of normal operation in a multipole discharge chamber. It is important that the cause of this preferential flow be understood.

The flow outward from a region of ion production in an otherwise field-free plasma is a well understood phenomenon. Some review of this process will be useful for the subsequent discussion of how the ion flow can be altered.

The potential distribution in the discharge plasma is determined by Poisson's equation. The important concepts can be demonstrated with variations in only one dimension. In one dimension, Poisson's equation is

$$\frac{d^2 V}{dx^2} = \frac{-\rho}{\epsilon_0} \tag{2}$$

where ρ is the local charge density and ϵ_0 the permittivity of free space. Assuming free access of electrons to all parts of the plasma, the electron density will be of the form

$$n_e \propto \exp(eV_p / T_e) \tag{3}$$

where e is the absolute electronic charge, V_p the local plasma potential, and T_e the electron temperature in eV. The mean free paths of the ions are normally large compared to discharge chamber dimensions. Therefore, the ions follow conservative paths with local velocity determined by the local plasma potential. Assuming negligible initial velocity when an ion is created from a neutral, which is reasonable for typical neutral temperatures, and defining plasma potential V_p so that zero is the effective origin potential of the ions, the ion density for flow in one dimension is of the form

$$n_i \propto j_i/(-V_p)^{1/2} \quad (4)$$

where j_i is the local ion current density. In practice, the ions do not originate at a single potential. There is, however, a narrow enough spread in origin potential that the density expression given above is a reasonable approximation outside of the ion production region.

Now consider a region of ion production, with drift spaces and negative potential surfaces to reflect electrons on both sides of this production region, as indicated in Fig. 5. Within the ion production region, the newly created ions with negligible initial velocity will result in a positive net charge density. From Eq. (2), a positive net charge density will result in a negative value for d^2V/dx^2, hence, a concave-downward potential variation in the ion production region. This potential variation serves to direct ions outward toward the bounding negative potential surfaces. The negative surfaces will attract the ions and potential disturbances will propagate back toward the ion generation region, thereby establishing the ion velocity in the drift region.

The equilibrium condition is one in which the ions are moving at the propagation velocity for a potential disturbance, so that disturbances can no longer propagate back toward the ion production region. This velocity can be found by equating the electron and ion densities. The resulting equation is differentiated with respect to plasma potential, then solved for the value of plasma potential that will permit plasma neutrality to be observed for small variations of potential about this value. Using these standard techniques, the value of plasma potential obtained is

$$V_p = -T_e/2e \quad (5)$$

which is, of course, both the energy per unit charge associated with ion acoustic velocity and the minimum ion approach velocity for a stable sheath solution.

The plasma potential in the drift regions, therefore, is established as $-T_e/2e$. With plasma neutrality at this potential, examination of Eqs. (3) and (4) will show that the net charge density of the plasma will be positive for $V_p < -T_e/2e$. Hence, the potential variation will be concave downward for $V_p < -T_e/2e$. For $V_p > -T_e/2e$, one might also expect a positive net charge density and a concave-downward curvature. But as the ion production region is entered, j_i in Eq. (4) is reduced and a net negative charge density and a concave-upward curvature are both permitted. These shapes are shown for the potential variation in Fig. 5, and have been described by Dunn and Self.[9]

Although large drift regions are indicated in Fig. 5, the same approach velocity will be established at a plasma sheath, as long as the sheath thickness is small compared to the dimensions of the ion production region.

Consider next the one-dimensional representation of a multipole discharge chamber in Fig. 6. The anode is on the left. The magnetic field near the anode comes next, followed by the ion production region. On the right the potential drops sharply for the plasma sheath at the ion optics. From the discussion in connection with Fig. 5, it should be evident that the ion velocity at the edge of the ion optics sheath is the ion acoustic velocity.

The conditions near the anode differ sharply from those near the ion optics. There is a magnetic field region, with an electron current to the anode through this field. Consider first the consequences of assuming that the approach velocity of ions to the magnetic field is the ion acoustic velocity. With the magnetic integrals used in most multipole designs, the ions will pass through the magnetic field, essentially unimpeded. Therefore, Eq. (4) may be used for ion density. The electron flow, however, is impeded by the magnetic field. Within the magnetic field, then, the electron density will always be less

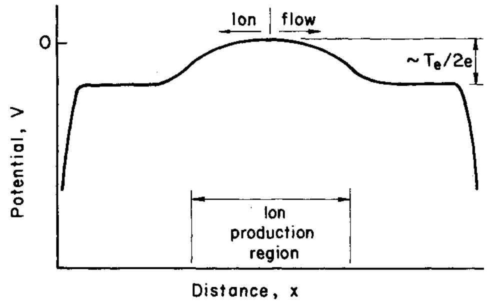

Fig. 5 Schematic variation of plasma potential with localized ion production region.

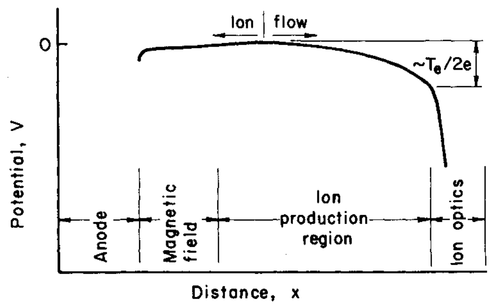

Fig. 6 Approximate variation of plasma potential through multipole discharge chamber.

than that given by Eq. (3). The appropriate constants for Eqs. (3) and (4) can be determined outside of the magnetic field region from the requirement for neutrality in the plasma approaching the ion optics at ion acoustic velocity. Given these constants, it can be shown that no plasma potential will permit plasma neutrality if 1) the current density of ions, j_i, is the same as at the ion optics, and 2) the electron density is reduced from that given by Eq. (3). Having assumed ion acoustic velocity for the approach to the magnetic field, item 1 must be true. However, the extent of the magnetic field is sufficient that neutrality must be observed within this region. If electron and ion densities cannot be equal, then the assumption of ion acoustic velocity for the approach to the magnetic field cannot be valid.

The velocity of ions approaching the magnetic field cannot be greater than the ion acoustic velocity, because the required plasma neutrality could not be obtained with a net charge density always greater than zero. Thus, only an approach velocity less than the ion acoustic velocity can be considered for a steady-state solution.

Experimentally, it is known that there are no large potential variations in the magnetic field region, with the possible exception of the sheath close to the anode. It is also known that the electron density must vary by a large amount in this region to account for the observed diffusion of electrons.[8] From quasineutrality, the ion density must vary in a similar manner. For the ion density to drop sharply as the anode is approached, the ion velocity must be greatly increased [see Eq. (4)]. At the same time, after being increased, it must still be below the ion acoustic value. These conditions can be met only if the ion approach velocity to the magnetic field is small compared to the ion acoustic velocity.

Returning to Fig. 6, if the ion approach velocity to the magnetic field is small compared to ion acoustic velocity, then the potential maximum in the ion production region must be located close to the magnetic field. As a consequence, most of the ions generated in the bulk plasma must be directed away from the magnetic field and anode.

If the particular anode portrayed in Fig. 6 is assumed to be made inoperative by reducing it to cathode potential, the process will be changed drastically. Because there would be no significant flow of electrons through the magnetic field, the electron density would again agree with Eq. (3). The mechanisms for establishing ion acoustic velocity then would be operative and the potential maximum would shift to divide the flow of the ions that are generated more equally. We can now return to the requirement for plasma neutrality within the magnetic-field region. With fewer ions directed toward the magnetic field, the value of j_i in Eq. (4) must be reduced near the magnetic field, in comparison with the value near the ion optics. This reduction in ion current density makes the matching of ion density with the reduced value of electron density within the magnetic field possible.

Expressed in the most general terms, then, the ion flow to the boundary of an ion production region can be altered by the combined effects of a magnetic field and an electron current through that field. With electron diffusion constrained by the magnetic field, the ion approach velocity to the magnetic field can be reduced to a value that is small compared to ion acoustic velocity. Removing either the magnetic field or the electron current through it will result in a tendency to re-establish ion acoustic velocity.

Relation of Model to Previous Observations

In the past, it has been a convenient assumption that ions will flow equally in all directions away from a region of production within a discharge chamber. This assumption was justified first by an experimental study by Masek,[10] which showed that the ion arrival rate at the boundaries of a particular discharge chamber were in approximate agreement with ion acoustic velocity for all boundaries. Later the ion production was identified with the primary-electron region, and maximum utilization calculations were found to be consistent with the assumption of uniform ion current density everywhere on the boundary of the primary-electron region.[11] This assumption of constant ion current density at the boundary of the primary-electron region has been used more recently to estimate discharge losses.[1]

In point of fact, there have been few actual measurements of ion current densities at the boundaries of a discharge chamber. At the same time, there were a number of clues that the ion arrival rate might be quite nonuniform.

It is well known that the discharge losses of a simple axial-field thruster continue to decrease with increasing magnetic field strength, above the field strength necessary for primary-electron containment.[12] This result is consistent with the increased radial impedance resulting in a reduced radial electric field, hence preferential ion direction to the ends of the discharge chamber.

More recently, with a multipole discharge chamber, a reduction in active anode length was directly correlated with increased discharge losses.[13] This result was particularly puzzling, inasmuch as the magnetic field above the inactive anodes was not altered. The ability to contain primary electrons therefore was not impaired, and the ion generation should have been unaffected

Even the comparison of discharge losses for different chamber length-to-diameter ratios was probably skewed by the wide use of propellant introduction at the chamber end opposite the ion optics. This introduction mode almost certainly led to a shift of ion generation toward the rear of the chamber, resulting in increased ion losses to the walls, thereby giving performance more consistent with the assumed equal distribution of losses. Actually, it has been known for a long time that propellant introduction closer to the ion optics can often significantly improve performance.[12]

In retrospect, then, it is clear that the general assumption of uniform ion losses in all directions was not justified. Instead, significant departures from uniformity have probably existed for a wide range of discharge chamber designs. These nonuniformities would have been noted if the results of previous experiments had been examined closely enough, or if proper instrumentation had been used to measure the actual ion-loss distributions.

Design Considerations

For design of a multipole discharge chamber, a volume ion production loss of 70-80 eV/ion is suggested for argon and operation near the discharge loss "knee." Use of multipole structures at all boundaries except the ion optics should result in ion-loss current densities at these structures of roughly one-quarter that at the plane of the ion optics, assuming either a small length-to-diameter ratio for the chamber, or propellant introduction close to the ion optics.

Note that this volume loss of 70-80 eV/ion is greater than that proposed earlier,[1] but the earlier work assumed higher ion flows to the multipole boundaries than can now be justified. It should also be apparent that interruptions of the pole-piece structure should be avoided, if at all possible.

Most of the investigation described herein applies directly to a multipole discharge chamber. There are some obvious applications, though, to other types of chambers. If one examines line-cusp discharge chambers, of the type introduced by Limpaecher and MacKenzie[14] and Crow et al.,[15] one finds that a similar ion flow model should apply. In the line-cusp source, in which the entire discharge chamber wall (except for the ion optics) becomes the anode, the magnetic fields must be considerably stronger than those used in the present investigation. This is because electron flow must be constrained parallel to the magnetic field, as well as normal to it. At these high field strengths, electron current densities should be small everywhere except near the cusps. As shown by the factor of several ranges for magnetic integral investigated herein, the transverse field regions should still be effective in directing ion flow away from the anode as long as an anode potential surface is located beyond the transverse field. This viewpoint is supported by experiment (Fig. 3) for very small conducted currents.

Most of the electron current for the discharge in a high field strength cusp design will be conducted near the cusps. To properly contain primary electrons, the field strength near the cusp should constrain electron flow, through both magnetic mirror effects and limited conduction area. With the use of a high enough magnetic field strength, then, a density gradient should also be introduced near the cusps. This density gradient should thus serve to direct ion flow away from cusp regions, as well as the other regions.

Concluding Remarks

Preferential ion flow has apparently existed in many discharge chamber configurations. The conditions necessary for preferential ion flow away from a discharge chamber surface are an electron current toward that surface and a magnetic field strong enough to affect the electron density, and, hence, the ion density, through interaction with the electron current. These conditions are met for most of the discharge chamber wall (except for pole pieces) in a multipole design. For a strong enough field strength these conditions can be established over the entire anode surface of a line-cusp design.

Acknowledgment

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