wave pattern had become fairly well developed. The body is moving toward the far end of the tank at the top of the photographs. Motion pictures were also made of the towed model flows at 64 frames/sec for Alfvén numbers of 0.26, 0.52, and 0.91; the wave angles were determined from measurements made on an optical comparator of a number of frames from each sequence.

Figure 17 is a photograph made with the cover on the tank. It shows quite clearly the deflection of the rubber sheets as the body is towed along the tank. The wave angles were determined with most certainty from the surface-wave measurements, however. Therefore Fig. 17 is included merely to show the two-dimensional disturbance waves in the tank.

C. Conclusions

Thus, we have observed forward-inclined disturbance waves, whose angles were predicted accurately by a method of analysis that parallels the analysis upon which the discussion of forward-inclined waves in MGD is based. We conclude that the picture of forward-facing waves and possibly upstream wakes, which has been presented in the literature, is probably correct.

The close agreement of the measured wave angles with their calculated values lends weight to the assertion that the EHD wave pattern is unaffected when the cover is removed from the tank in order to permit surface waves to reveal the EHD flow structure. Rigorous justification is possible if the wave-velocity analysis for the case of free surface EHD shows that there is no appreciable coupling between EHD waves and surface waves, but this has not been done at this time.

It might be possible to alter the model to include the study of finite electrical conductivity by perforating the elastic sheets. The size and density of holes would determine the rate of diffusion of the fluid across the field lines and hence the analog conductivity.

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Evaluation of Electrode Shapes for Ion Engines

S. L. Eilenberg,* W. Seitz,† and E. Caplinger†
Electro-Optical Systems, Inc., Pasadena, Calif.

Techniques for evaluating electrode geometries for use in ion engines are presented. These techniques include the employment of a digital-computer program and an electrolytic tank. The study is separated into several problem areas, which include 1) direct interception, 2) charge-exchange interception, 3) uniformity of emission, and 4) beam collimation. Direct interception is discussed in terms of unsealed, sealed, and deactivated edges. The perimeter of the sastrugi geometry has been given special attention for focusing the outermost beams. Charge-exchange trajectories have been calculated. Because of the slope of field near the accel-aperture in an accel-decel system, the charge-exchange erosion pattern has features which distinguish it from direct interception. The consequences of this form of erosion are discussed. A possible solution to this problem is presented. The sastrugi geometry has some features that inherently produce nonuniform emission over part of its surface. The advantages and disadvantages of this characteristic are discussed, and electrolytic tank studies are described in which higher degrees of uniformity may be achieved if desired. In addition, digital-computer results are presented showing the wide variation of current densities over the sastrugi ionizer if full space-charge limited flow is achieved. The effect of the shape of the beam-plasma boundary on ion trajectories is also discussed.

Introduction

PRACTICAL ion engines for use on space missions must be designed to operate with long endurance capability. One of the most important areas to be considered in the design of such engines is that of electrostatic optics. It is necessary to determine the shape of electrodes which will produce the highest average current density and the lowest amount of particle interception on electrode surfaces. The need for a high average current density is dictated by the power efficiency requirement. This efficiency depends upon the ratio of the beam power emitted to the heat radiated per unit ionizer area. The higher this ratio, the more efficient the operation of the engine. It is also necessary to consider

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* Senior Scientist, Ion Physics Department. Member AIAA.

† Physicist.

the degree of uniformity of emission that is required. The question arises as to whether the current should be emitted uniformly or whether it is possible to obtain efficient operation with the current density varying widely over the ionizer surface.

Beam Interception

The beam interception with electrode surfaces consists of two types. First, there is the direct interception of ions which originate at the ionizer surface. This interception can occur as a result of improper design (where a particle trajectory is intersected by an accel structure). Alternatively, it can be due to thermal spreading of the beam. In the latter case when one takes into account the additional transverse motion due to a thermal Maxwellian distribution of the ions, there is a finite amount that will intercept. (Theoretically, there is at least one particle that approaches infinite transverse velocity.)

A second type of interception (which may be called indirect interception) is due to scattering collisions. These scattering collisions occur between the accelerated ions and neutral atoms extant in the interelectrode space. These atoms occur because a small fraction (of the order of a few percent) of the particles escape from the surface as neutral particles. When an ion collides with one of these particles, it produces a charge-exchange event. Of all of the atomic interactions, charge exchange has the highest cross section (the highest probability of occurrence) wherein a fast ion exchanges charge with a slow atom. The ion changes into a fast neutral particle and travels on in its initial direction. The newly charged atom would then be accelerated from rest by the electric field in the interelectrode region. However, its trajectory would differ from the trajectories of any of the original ions since it originates in the interelectrode space rather than on the surface of the ionizer. Some of these new ions will be accelerated into space and some will intercept the accel electrode. The path that they follow depends upon the point of origin of the charge-changing event.

Closure Surface and Neutralization

If the beam is properly neutralized the particle trajectories should be very rectilinear. If it is partially neutralized these will tend to spread, and if it is completely unneutralized a virtual cathode will form and reflect the trajectories back toward the source.

In the typical ion engine there is an ionizer above ground potential which thermally emits ions, an accel electrode below ground which creates an attractive field producing high current densities, and a decel electrode essentially at ground which causes the ions to assume the velocity required for the mission. It has been found experimentally, however, that it is possible to eliminate the decel electrode since the beam (when properly neutralized) will form a plasma which nearly extends to the downstream surface of the accel electrode. Beyond this downstream surface there will be a decelerating field that terminates in what appears to be a ground potential surface.

This ground potential surface may be called a meniscus or closure surface of the downstream plasma. It has also been found experimentally that this surface may assume unusual shapes depending upon the degree of neutralization and the current density. This shape strongly affects the trajectories of downstream particles and consequently the amount of thrust that is produced.

Solving the Problem

These phenomena can have a strong influence on the performance of an ion engine system. One must consider them in as quantitative a fashion as possible in order to obtain the specific electrode shapes.

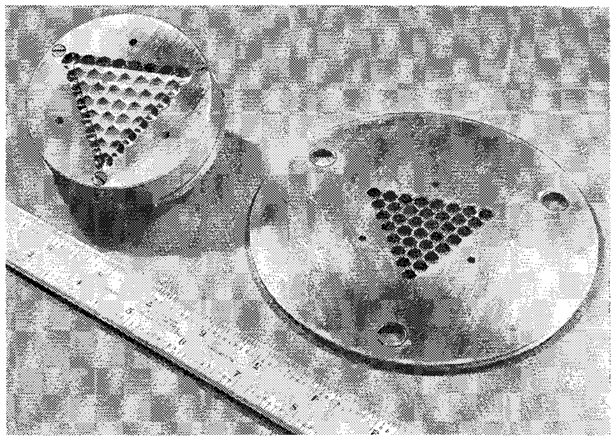

Fig. 1 Sastrugi electrodes.

A considerable amount of success has been obtained in the past by rather intuitive and experimental techniques coupled with analytical studies for obtaining electrode geometries. It was fairly simple to obtain a geometry (if the current density requirements are not too high), which would collimate a beam so that it would pass through an aperture. In fact, if it did not pass through initially, it was found that the beam would erode the aperture until it did fit, after which the erosion rate will drop significantly.

The phenomenon of charge-exchange erosion has not been particularly significant until recently. It is a second-order effect, and the consequences are not noticeable until operation extends to 1000 hr or very high current densities over a significant period of time. Now, however, ion engine performance is reaching the point where the techniques of optical design must be considerably refined.

Techniques for Electrode Design

Analytical Techniques

One approach to the design of electrode structures for the projection of ion beams is related to the work done by Pierce.[1] In this technique, one obtains solutions to the equations for space-charge limited flow between regular geometries such as concentric spheres, concentric cylinders, and parallel planes. From these a potential distribution is obtained for an infinite, or completely closed, region of space-charge limited emission.

When an actual electrode system is being designed, it is one in which the total emission is spatially limited; i.e., the infinite plane would be a finite area, or the concentric sphere would be a segment of a sphere. One must then calculate the potential distribution for a beam in the infinite case and place specially shaped (focusing) electrodes adjacent to the finite beam that will produce the same potential distribution along its edge. This being a self-consistent field solution, the dynamics of the finite-shaped beam will be the same as for the infinitely extended beam.

This technique has limited application because it assumes uniformity of emission and regular surfaces. Recently developed geometries such as the sastrugi are more complex and have certain characteristics that limit the application of this technique.

The main technique employed by the authors has been the use of a computer program for obtaining ion trajectories. It is believed that there is too much uncertainty in the form of the beam to depend solely upon a potential matching technique. Nevertheless, the latter technique is used to obtain initial design information, e.g., for extending the uniformity of emission over a given geometry. Thus, the over-all techniques employed include the use of a computer program for treating ion optics (including space charge) and an electrolytic tank for obtaining preliminary geometries.

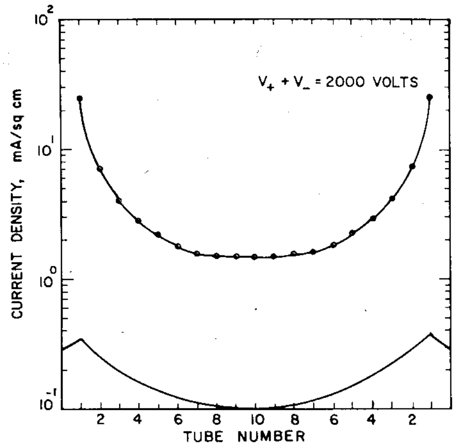

Fig. 2 Sastrugi space-charge limited current profile.

Sastrugi Optics

In the early development of ion engines, the main concern was the design of a device that would produce some level of thrust. As a result, these engines were in the form of small-disk or narrow-strip ionizers surrounded by large focus and accelerating electrode structures. Later on, emphasis was placed upon high thrust density, power efficiency, and the attainment of 10 mlb or more of thrust.

To achieve this thrust level, it would be necessary to have a multiplicity of disk-shaped ionizers or a multiplicity of strip ionizers. A considerable amount of thrust density would be lost, however, since the space given to focus electrodes would not be ionizing. As a result, in the case of the disk emitters, a highly integrated engine was designed in which the disks were embedded in a single plate, and considerably reduced focusing structures were placed between them. This is essentially true for the case of the strip engine development also.

Difficulties were found in the use of these focus electrodes, however. They emitted some ions and did emit a lot of radiant energy even though they were shielded. Secondly, because they were hot (slightly cooler than the ionizer structure), they would produce ions having trajectories that would intercept the accelerating structure. In the case of the parallel strip engines, the approach was to find ways of cooling the focusing electrode structure.[2] For the multidisk engines, the approach was to make the whole frontal area ion emitting and provide ion focusing by suitable surface contouring. The contouring was accomplished by machining an array of spherical depressions intersecting in such a fashion that there would be no flat areas. An example of such an emitting surface and the accelerator electrode is shown in Fig. 1. A corresponding design for strip emitters, the fluted emitter, has been employed as discussed in Ref. 3.

Several questions arise with regard to this concept of ionizer surfaces. First, without a focus electrode between adjacent emitters, is it possible to cause the beams to be focused through their given apertures? Second, since it is impossible to have an infinitely sharp ridge (or peak) between these emitting regions, how much can the direct interception due to these ridges be reduced?

The answer to the first question can be obtained through a study of trajectories from the entire surface. The question of the ridge region depends to some degree upon how sharp the ridges can be made and secondly, upon the cesium flow that actually reaches this region. Thus it is necessary to determine trajectories and also to determine the cesium flow for a given ionizer structure and contour.

There is a very basic difference between sastrugi geometries and any geometry that incorporates a focus electrode, particularly a focus electrode that is at the same potential as the ionizer. This can be illustrated in the following discussion.

In considering a simple parallel plate diode under fully space-charge limited operation, each line of force from the accel must end on a space charge. Therefore, the more lines of force, the more current since the field at the emitter is zero for fully space-charge limited emission. Next consider the effect of changing this geometry into a sastrugi shape, and for simplicity of cross section assume that the shape is in the form of strip emitters. If additional focusing is attempted by placing focusing electrodes opposite the ridges of the sastrugi, some of the lines of force from the accel will land on the focus electrodes rather than on the space charge. Thus, for a given voltage and a given spacing, the total amount of current is reduced by this amount.

There is an additional disadvantage, since the spacing between the emitter potential and the accel potential is reduced by the amount occupied by the focus electrode. This reduces the voltage that may be applied, considering breakdown and thermionic emission from the accel, and it is clear that even less current density is available due to the presence of the focus electrode. Going to a sastrugi configuration minimizes these disadvantages but with the result that the emission density becomes very great as one progresses toward the ridge. This nonuniformity of emission has an effect on the manner in which one can design the electrode system.

Computer Program

The original program was formulated at the NASA Lewis Research Center.[4] A detailed description is contained in Ref. 5. Basically this program consists of solving N order equations by writing down the matrix expression and arriving at a solution by an iterative technique. There are other methods for obtaining the solution such as relaxation calculations.

The program from NASA was then modified since that program was for annular geometries. One of the changes consisted of extending the program to include the axis of the annulus. The sastrugi array was then treated by assuming certain symmetry properties. It was assumed that the hexagonal shape of a sastrugi element could be approximated by a circle. In actually studying any given geometry, two circles are considered; namely, one which circumscribes the hexagon and one which is inscribed by the hexagon. It can be seen that these correspond to intersection with the peaks and ridges, respectively, of the hexagonal sastrugi. It is also assumed that the transverse fields vanish at the boundary of the hexagonal array. Thus the problem being solved is really one of a circular area surrounded by an annular arc. The real accel apertures are circular and so are simulated exactly.

The original program solved the case in which the emission was space-charge limited over the entire surface of the emitter. As discussed previously, the current density varies considerably from the center to the edge of the sastrugi emitter. It can be shown theoretically that at the very edge (where the peak is infinitely sharp) the density goes to infinity. A further modification was made to account for this partial space-charge limited operation over a portion of the ionizer. This is a more realistic picture of an actual ion engine. Other modifications were made in the program. For example, it is possible to calculate the trajectories of any "secondary" charge particles whether produced in a charge-exchange collision or by thermionic emission from an electrode. It has been possible to study many aspects of the sastrugi geometry through the use of the revised program.

Electrolytic Tank

Through the use of this tank, studies have been made for obtaining initial designs with more uniform emission over the surface. The standard technique for designing Pierce-modified electrode geometries is used. However, an approximation is made in that the focus electrode replaces part of the ionizer surface. Normally, a geometry of this type is designed by assuming that the emission is space-charge limited within the cylindrical, spherical, or planar region. Then a nonemitting electrode is placed at the boundary which produces a potential distribution corresponding to the theoretical value for space-charge limited emission for that configuration.

The present technique consisted of an arrangement wherein the interior part of the ionizer surface is spherical or planar, whereas the outer portions are modified in shape to produce a potential distribution that matches that for space-charge limited flow in the interior region. This is an approximation since emission actually occurs in this outer "focus electrode" region.

This type of design does distribute the current density more uniformly over the central regions of the sastrugi element. It is impossible to maintain uniform distribution to the peaks because the field goes to very high values there. However, the approximation is better than would seem since the cesium flow in an actual sastrugi emitter is reduced near the peak; this reduces the emission density considerably from the theoretical fully space-charge limited value.

Various techniques have been used by the authors in the design of ion optical systems for ion engines. However, the most worthwhile has been the use of the electrolytic tank to produce initial geometries with nearly uniform emission, when desired, and then to evaluate these geometries with the computer program to determine the current density and the resultant ion trajectories. The computer program has also been very useful in studying the areas of accel erosion due to charge-exchange collisions and in determining the power distribution at the ionizer surface caused by secondary emission from the accel electrode.

Results of Ion Optics Studies

Uniformity of Emission

The first concern in the study of sastrugi optics was in the degree of emission uniformity produced by simple sastrugi geometries such as that shown in Fig. 1, where the depressions are spherical. A typical sastrugi geometry was evaluated for fully space-charge limited emission (Fig. 2). Figure 2 shows the plot of current density vs distance across the sastrugi area. Note that the current density assumes very large values near the peaks and reaches a minimum at the center of the sastrugi. The calculated perveance of this geometry was 11 nanopervs (11×10^{-9} amp/$v^{3/2}$).

In an actual ion engine the feed of cesium to the front surface is relatively uniform across the sastrugi area. Under these conditions, it is clear that the current will become space-charge limited at the center of the ionizer and be emission limited everywhere else. Attempts to increase the current density above this level would cause flooding of the central portion of the ionizer with an undesirable increase in the neutral flux. The space-charge limited emission over just a small region of the ionizer represents a waste of the lines of force from the accel structure. Potentially, much more current could be obtained if the cesium flow were tailored to the space-charge limited emission distribution.

An alternative to tailoring the cesium flow is to modify the surface of the sastrugi so as to make more of the lines of force move towards the center of the sastrugi area. This can be accomplished by increasing the radius of curvature at the center of the sastrugi element and decreasing it toward the edge. This cannot be carried on indefinitely because the lines of force do tend to congregate considerably at the peak. Thus, the uniformity of emission may be improved over the surface of the sastrugi, and higher total current may be obtained but only to a certain point.

An electrolytic tank study was made of geometries that produce more uniform emission. The corresponding current density distribution over a flattened geometry is shown in Fig. 3. Note that the uniformity of emission has improved over Fig. 2. However, the emission still goes to infinity near the peaks of the focusing regions. This design has a calculated perveance of 7.82 nanopervs.

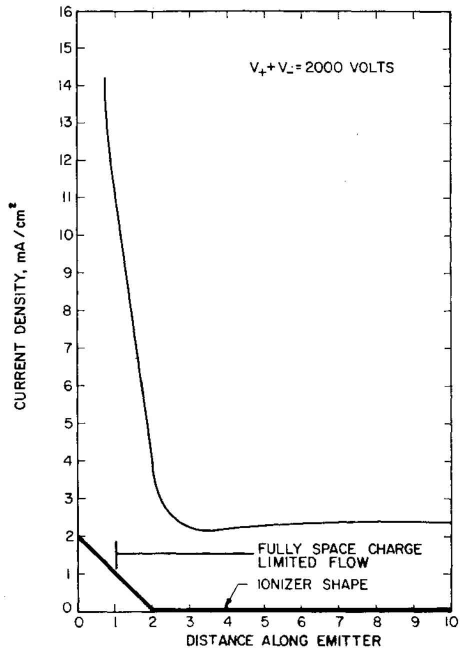

Fig. 3 Flatbottom ionizer current profile.

Cesium Flow Analysis

As mentioned previously, one might tailor the flow of cesium through the ionizer to correspond to the emission current density for full space-charge limited emission. Studies of the flow of cesium through a porous material can be made with the use of the electrolytic tank if one assumes free molecular flow. The justification for this assumption is presented below. The flow problem is set up in the tank with the front and back surfaces of the ionizer considered to be equipotentials. It can be shown from considerations of electrostatics that in a vertex region of a central angle the field strength drops to zero if the angle is less than 180°. Conversely, for a convex central region, the field strength goes to infinity. Using these considerations, a plot was obtained for the cesium distribution (Fig. 4).

Obviously, the cesium flow distribution tends in an opposite direction to the current density distribution. By suitably reshaping the back of the ionizer or inserting nonporous areas, the flow of cesium to the front surface can be modified considerably. However, the match must always be poor at the edge of the sastrugi surface since the current density tends to infinity, and the cesium flow density tends to zero.

Thus, in practice the true relative performance of geometries is strongly a function of the cesium flow distribution. Con-

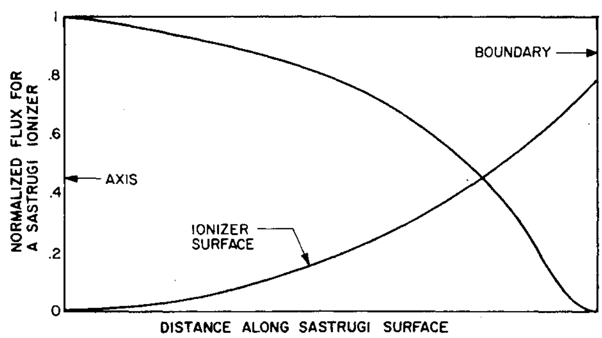

Fig. 4 Particle flux vs distance along sastrugi surface.

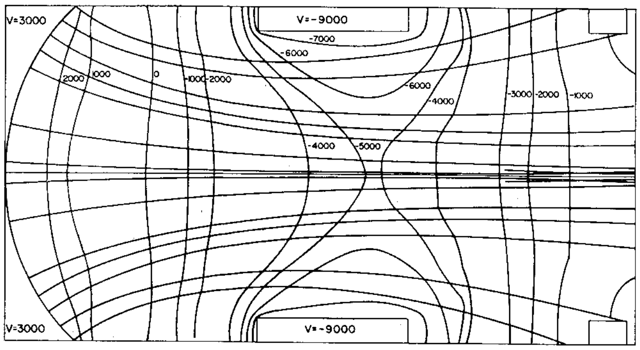

Fig. 5 Sastrugi ion trajectories (fully space-charge limited flow).

sider the two geometries mentioned previously and assume a uniform distribution maintained over 80% of the ionizer area. Let this distribution have a value corresponding to the minimum calculated current in the fully space-charge limited current curves in Figs. 2 and 3; then the perveance of the spherical design would be 1.44 nanopervs, whereas that of the flat-bottom geometry would be 2.76 nanopervs. This is a 92% improvement for the latter design. The space-charge limited perveance for the spherical geometry can vary anywhere from less than 1.44 to a theoretical maximum of 11 nanopervs depending upon how much the cesium flow matches the current density.

Although the new directions for design geometries described in this paper are expected to result in higher performance than presently available, the simple sastrugi designs give higher performance than the earlier nonsastrugi surfaces.

Interception Problems

Another point of concern in connection with sastrugi geometries is the degree to which direct interception would occur, particularly interception produced by particles originating near the peaks of the sastrugi geometry. It is clear that a particle that is emitted exactly at the peak will follow the line of symmetry between two sastrugi elements and directly impinge on the accel electrode. If the radius of curvature of this peak were infinitesimally small, then the impinging beam density at the accel surface would be small. However, since there is a finite radius of curvature, one is concerned as to how far down the slope ions are emitted which do produce interception.

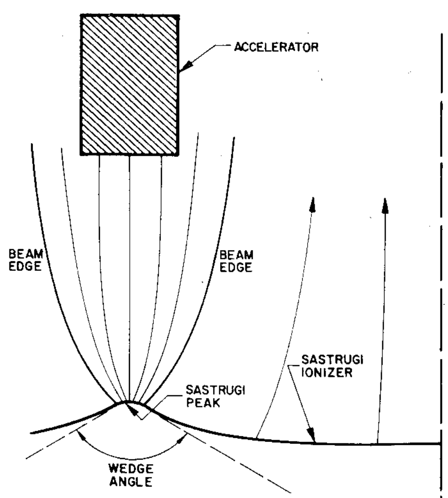

Fig. 6 Ion emission at sastrugi peak.

Figure 5 shows trajectory distributions for a simple sastrugi geometry. The trajectory starting near the edge of the sastrugi, at a distance small compared with the known minimum radius of curvature, is seen to clear the accel substantially. The trajectories are plotted for full space-charge limited emission so that the divergence of this particular trajectory represents a maximum. It is a rule of thumb that, if the outermost trajectory clears the accel electrode by 10% of the average electrode spacing, the interception due to thermal distribution of velocity of the ions will be on the order of several parts in 10^5. Thus, the clearance of trajectories from an infinitely sharp sastrugi edge is substantial for this geometry so that in an actual engine the erosion will be down to acceptable values.

A second part of the interception problem relates to the fact that the sastrugi edge or peak not only does not focus well but does emit a certain amount of ions. The radius of curvature of typical sastrugi edges is on the order of one mil. Assume that the trajectories of the particles that are emitted from this spherical-or cylindrical-shaped surface uniformly spread themselves between the two edges of adjacent beams (Fig. 6). One can then determine that the impingement density on the accel electrode is reduced to about 3% of the emission density at the sastrugi edge. This represents an upper limit, however, since the cesium flow distribution to the surface of the ionizer drops off and ideally goes to zero for an infinitely sharp edge. The impingement density from an unsharp edge can be obtained in the following manner.

Within the ionizer the cesium vapor density is low enough that vapor transport occurs mainly by molecular flow. Since for molecular flow the flux vector is proportional to the cesium vapor density gradient, it follows that for steady-state flow the concentration of cesium in the ionizer obeys the Laplace equation. For a typical sastrugi, including edge angle, and assuming that the cesium is uniformly distributed over the edge region, the resultant analysis shows that the direct interception density on the accel due to the flow-through particles is about 10^{-4}. Thus the direct interception by flow-through cesium at the sastrugi edge is negligible.

Also of concern are the unionized cesium atoms, which when emitted, bounce off the accel electrode, return to the sastrugi peaks ionized, and finally intercept the accel electrode. Using the previous assumptions, the level of this interception is computed to be on the order of 5×10^{-4} which is still too large.

It is clear, therefore, that the sastrugi edges may have to be specially sharpened or deactivated to produce the minimum electrode erosion that is required for maximum life of an operating ion engine. However, fairly long periods of operation may be achieved without doing this. Furthermore, in lieu of deactivating the ionizer peaks, the accel electrodes may be conditioned in certain ways to reduce the erosion that does occur. Studies of the problem of accel erosion as a function of the materials used are discussed in Ref. 5.

The early computer studies were for fully space-charged limited emission. Recently some results have been obtained for partially space-charge limited emission. In particular, the results (as shown in Fig. 7) show the type of beam that is obtained when the emission is space-charge limited at the center of the emitter and is emission limited near the bounda-

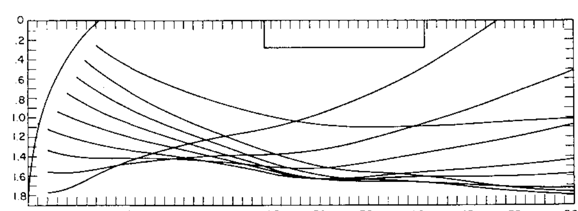

Fig. 7 Sastrugi ion trajectories (partially space-charge limited).

ries of the geometry. A nearly uniform current distribution was used in this calculation. Thus, this is a more realistic picture, as far as the trajectories in an actual engine are concerned, than that for fully space-charge limited emission.

Note that the outer trajectories are somewhat more convergent than in the case of fully space-charge limited emission. Note also that there is a set of trajectories that start near the center of the emitter, diverge considerably, and actually become the outer envelope of the beam further downstream. The net result of this is to produce a hollow beam that has been observed in actual engine operation. This indicates that the distribution of cesium flow chosen for computer simulation is fairly representative of actual engine operation. (The divergent behavior does not present any serious problem for clearance of the accel electrode since it takes place beyond the accel electrode.)

The divergence from the center of the ionizer can be explained by the fact that this region has considerable space charge since it is near full space-charge limited operation whereas the regions further out have considerably less. Under this condition the equipotentials tend to expand away from the ionizer surface in this region. This produces a divergent field near the axis which causes the trajectories to expand.

On the other hand, the integrated space charge over the ionizer surface is reduced (for a given voltage across the system), and the edge trajectories do not experience as much of a divergence. Thus, the net effect is as one might expect; the convergence of outer trajectories and divergence of inner trajectories resulting in a hollow character in the beam distribution.

Indirect Interception

A very basic limitation on the life of an ion engine is imposed by the interception of ions that result from charge-exchange collisions. The computer program has been used to obtain trajectories of such ions to determine the extent and the pattern of erosion produced by this effect. The results of one of these studies is shown in Fig. 8a. In an accel-decel system, where the potential distribution is as shown in Fig. 8b, the accel electrode acts as a trap or sink for charge-exchange ions. This results in those charge-exchange ions produced in the aperture region being accelerated to the sides of the aperture. The ions created in the upstream region are accelerated to the downstream surface of the accel electrode; and because the downstream region of the beam is a reverse

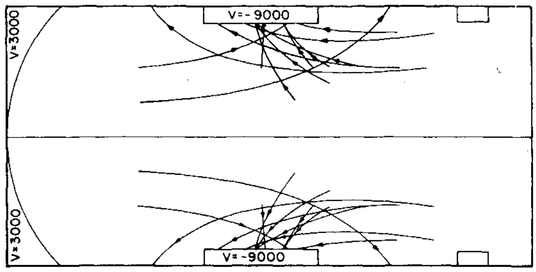

Fig. 8a Charge exchange on trajectories.

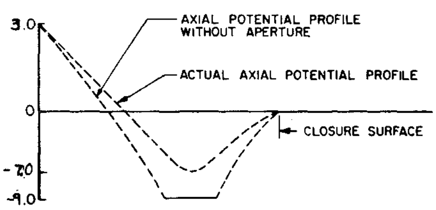

Fig. 8b Schematic of potential profile along axis of geometry.

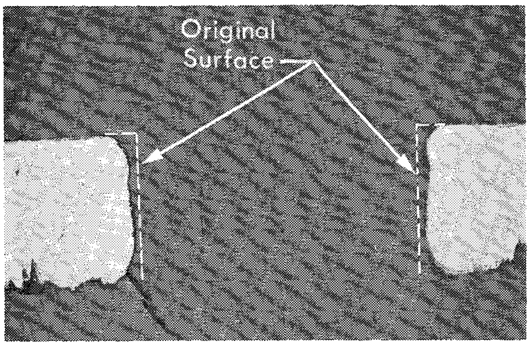

Fig. 9 Charge-exchange ion erosion.

field, ions formed there are accelerated through the aperture to the upstream side of the electrode.

Of particular interest are ions formed in the aperture region. Here the particles are actually focused preferentially toward a particular portion of the aperture because of the curvature of the field. This results in a "bathtub ring" erosion pattern that has been observed after engine runs. In fact, this ring was the first real charge-exchange erosion pattern distinguished in an operating engine (shown in cross section in Fig. 9). It serves as a rather useful bench mark in determining the extent of erosion over other regions where it is not easily distinguishable by its pattern.

When the accel-decel ratio approaches one, this pattern disappears. In fact, virtually all of the charge-exchange erosion disappears because the particles are accelerated out of the aperture, and there is no significant reverse field. Those which do impinge most probably have energies below the sputtering threshold.

A suggestion for reducing or eliminating the problem of erosion has been previously advanced.‡ This consists of inserting another electrode downstream of the accel electrode and at a more negative potential than the accel. Then this electrode will become the trap for the charge-exchange ions as opposed to the accel electrode (Fig. 10). Thus, in principle, all of the charge-exchange ions would intercept the second electrode until it is eroded away; then the accel electrode would begin to be eroded. This could increase the life on an ion engine by a factor of 2.

Further increases in electrode life could be accomplished by fabricating this electrode of materials (having a lower sputtering rate) which would normally not be used as an accel because of ionizer incompatibility. The material from an accel electrode can sputter on to the ionizer and then either remain on the ionizer or re-evaporate. This depends upon its vapor pressure-vs-temperature relationship. If the substance has a high vapor pressure (such as copper), then the ionizer will remain free of sputtered material. However, if the material has a low sputtering rate it generally has a low vaporization

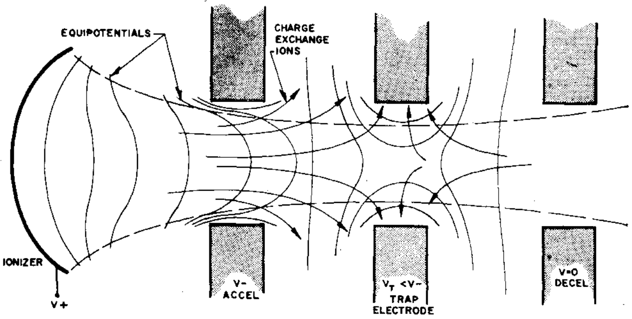

Fig. 10 Charge-exchange ion trapping concept.

‡ Conceived by S. L. Eilenberg while employed at Hughes Research Laboratories in 1961.

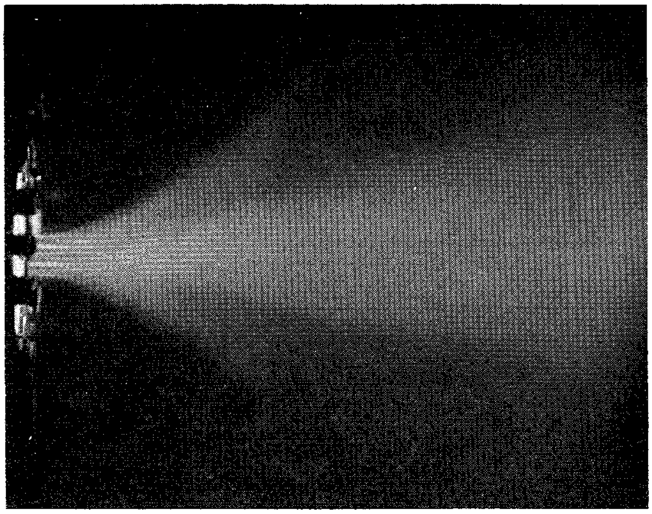

Fig. 11 Beam from experimental engine.

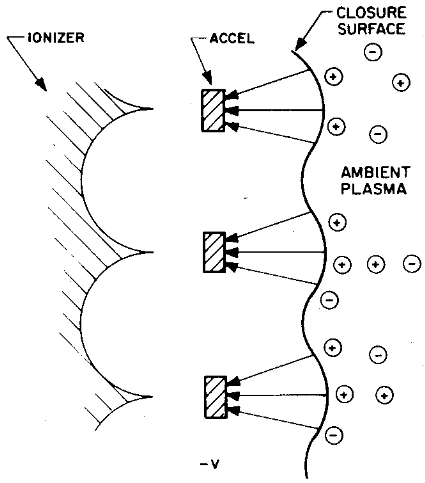

Fig. 12 Closure surface and resultant erosion.

rate, and there will be some point of equilibrium where the arrival rate is equal to the vaporization rate. The downstream electrode might be made of some refractory metal that would have a low enough arrival rate (including shielding by the accel) that the coverage of the ionizer could be kept to an acceptable minimum.

Closure Surface

As mentioned in a preceding section it is not necessary to use a decel electrode in an operating ion engine, particularly if the beam is neutralized. It has been observed experimentally that the beam is neutralized nearly to the downstream surface of the accel electrode. There is a region between the edge of the neutralized beam and the downstream accel surface where a decelerating field exists and terminates in a surface that is called the closure surface (since it encloses the beam plasma). There is experimental evidence to suggest that the form of this closure surface can strongly affect the collimation of the beam.

Analytical studies have been made on the position or location of the closure surface relative to the downstream surface of the accel electrode. The results of those analyses are presented in Ref. 5. In brief, the conclusion is that it is possible to obtain correlation between a simple one-dimensional analysis and observed results in an operating ion engine.

The calculation was performed under the following assumptions. First, it was assumed that at a stable closure surface the electric field is zero. This is justified because any nonzero field would result in a displacement of plasma electrons in the closure surface. Using the Poisson equation and the continuity equation, it was possible to calculate the position of the closure surface for this condition. It was also assumed that the potential of the closure surface was zero. Figure 11 shows the emergent beams of a sastrugi engine. If it is assumed that the closure surface is where adjacent beams overlap, the data agree well with the analyses. The reason for assuming this location for the surface follows.

The simplified analysis, being one-dimensional, merely determined the location of the surface. Details observed in the study of photographs of actual beams (such as Fig. 11) indicate that the closure surface under certain conditions is not flat. One can see that the emergent beams are nearly straight for some finite distance, then diverge very rapidly in an extremely short distance. This divergence can be explained by assuming that the closure surface or the zero potential bulges in toward the accel aperture and then bulges out, forming a converging surface between apertures (as shown in Fig. 12).

Additional support for this view of the shape of the closure surface was obtained when erosion was observed on the downstream side of the accel electrode in a narrow region between accel apertures (as indicated in Fig. 12). This could easily be caused by ions that are accelerated from the plasma to the accel electrode and that are focused by the concave part of the closure surface.

An alternative interpretation of this erosion was that the charge-exchange ions from the upstream region produced this effect. However, studies of charge-exchange trajectories do not indicate such a concentrated focusing of the particles. The computer program is being modified at the present time to determine more fully the shape of the closure surface.

Conclusions

The conclusions arrived thus far are as follows: 1) sastrugi optics inherently produce more average current density than a comparable system using focusing electrodes, 2) a sastrugi geometry possesses enough focusing properties to reduce the accel erosion to a reasonable minimum, 3) a certain degree of treatment must be applied to sastrugi ridges to insure that the erosion be kept to the point where 10,000 hr of operation is possible, 4) the charge-exchange erosion is a limitation but is one that may be substantially reduced, 5) the refinements in the design of optical systems involve the shaping of both front and back ionizer surfaces (in order to more closely match the space-charge limited current density and the cesium flow density profile), and 6) the effects of the space-charge limited current density distribution, the cesium flow distribution, and the closure surface are all of importance in the study of ion trajectories.

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