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AN ELECTRON BOMBARDMENT THRUSTER OPERATED WITH A CUSPED MAGNETIC FIELD

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16. Abstract

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SUMMARY

The performance of two 20-centimeter-diameter electron bombardment thrusters with an axial magnetic field and a superimposed cusp magnetic field was experimentally determined. The thruster lengths were 20 and 10 centimeters, respectively. The cusp field was added to suppress the anomalous diffusion phenomenon found in the discharge chamber of the thruster. Discharge performance and discharge noise measurements were obtained. Anomalous diffusion appeared to be suppressed by the addition of the cusp field; however, thruster performance was not enhanced.

INTRODUCTION

The magnetic field of the electron bombardment thruster is provided to lengthen the path of the energetic electrons in the discharge chamber in order to increase the occurrence of ionization collisions between the electrons and the propellant atoms. The electrons entering the discharge plasma gain most of their energy by accelerating through the plasma sheath that exists between the cathode and discharge plasma, the potential of which is nearly that of the discharge chamber anode. The electrons enter the plasma with this energy, gyrate around magnetic field lines, and eventually arrive at the anode as a result of random collisional processes. The highest discharge chamber efficiency (lowest energy dissipated per ion produced) is obtained when the maximum amount of discharge energy is expended in the plasma and little remains with those electrons reaching the anode electrode. From simple considerations this ideal condition is a function of the strength of the applied magnetic field. However, it has been found that increasing magnetic field strength beyond a critical value results in turbulent electron transport through the plasma - a departure from collisional transport (ref. 1). This turbulent transport, or anomalous diffusion, appears to limit the effectiveness of the magnetic field in the discharge process.

In reference 2 a stability analysis following that of the Kadomstev and Nedospasov instability for the positive column predicts that anomalous diffusion occurs in the ion thruster beyond a certain value of magnetic field strength called the critical magnetic field strength. The theoretical relation of the critical magnetic field strength to the discharge chamber diameter is the same as an experimentally determined magnetic scaling relation for the ion thruster. In reference 3 anomalous diffusion is investigated experimentally, and the results suggest that a stabilizing magnetic field configuration might be the solution for overcoming the phenomenon. In an experiment on a Penning-type discharge in which anomalous diffusion occurs (ref. 4), a stabilizing magnetic field was used, and decreased losses are reported.

The discharge chamber plasma of the electron bombardment thruster is similar to that of the Penning-type device. For example, both have axial magnetic fields, thermionic emitting cathodes, and cylindrical anodes, and both operate by electron bombardment in the same pressure regime. Both exhibit anomalous diffusion and emit low-frequency noise above a predictable critical magnetic field strength. When sufficient superimposed magnetic well or cusp field strengths are applied, two important results are reported in reference 4 which have possible consequences to electron bombardment thruster operation. First, the plasma noise that appears at electrodes immersed in the plasma is reduced, which indicates suppression of the anomalous diffusion phenomenon. Second, the electron containment characteristics in the range beyond the critical axial magnetic field strength are improved. With these results in mind, two electron bombardment thrusters were modified to include a cusp magnetic field, and thruster performance under a variety of operating conditions was evaluated.

THRUSTER PERFORMANCE

An electrical schematic for the thrusters used in this experiment is shown in figure 1. Thruster operation begins with the introduction of mercury propellant vapor into the discharge chamber. A mercury plasma discharge is created as a result of a flow of electrons from the cathode to the cylindrical anode of the thruster. The screen and accelerator grids extract, focus, and accelerate an ion beam. The discharge power supply maintains the anode to cathode potential difference and provides the energy for the ion production.

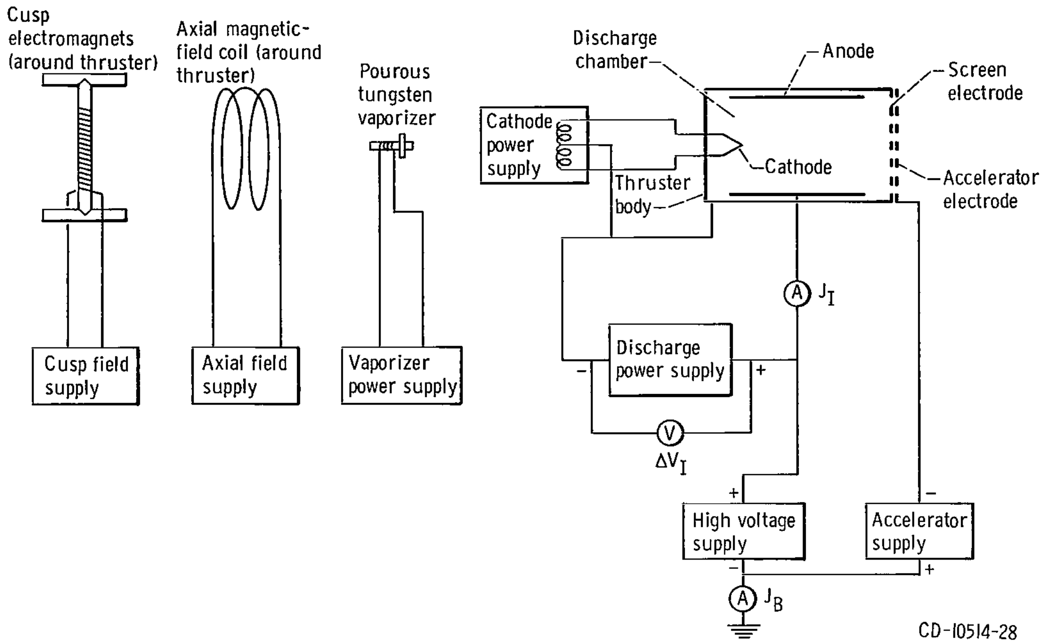


Figure 1. - Electrical schematic for electron-bombardment thruster.

The quantity used as a measure of discharge chamber performance, the discharge energy per beam ion (also referred to as eV/ion) is given by the equation

$$\mathrm{eV/ion} = \frac{(J_I - J_B)\Delta V_I}{J_B}$$

where ΔV_I is the discharge power supply voltage, J_B is the ion beam current, and J_I is the anode current (see fig. 1). The quantity $(J_I - J_B)$ is the current through the discharge power supply and when multiplied by ΔV_I gives the discharge power. The eV/ion is a strong function of the applied magnetic field primarily because of its influence on the electron trajectories in the discharge chamber.

APPARATUS AND PROCEDURE

Thrusters with Cusp Magnetic Fields

The thrusters tested are shown in figures 2 and 3, respectively. Both are electron bombardment thrusters of 20-centimeter anode diameter. The primary difference be-

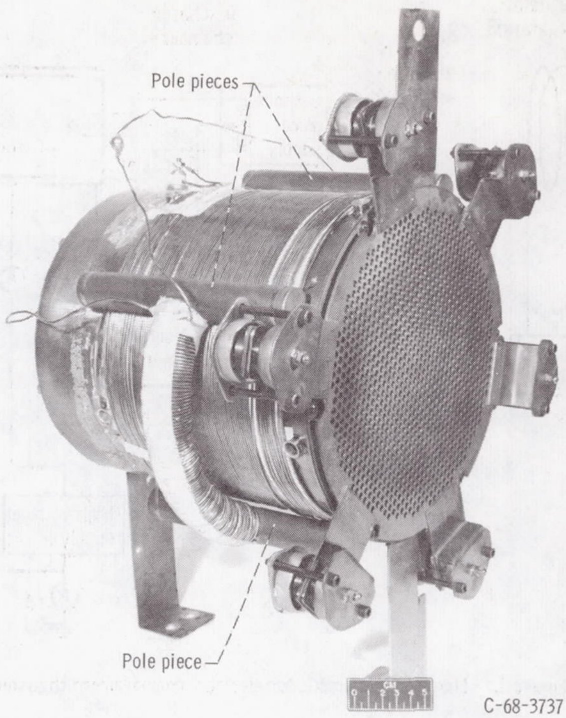


Figure 2. - Thruster 1. Discharge chamber length, 20 centimeters.

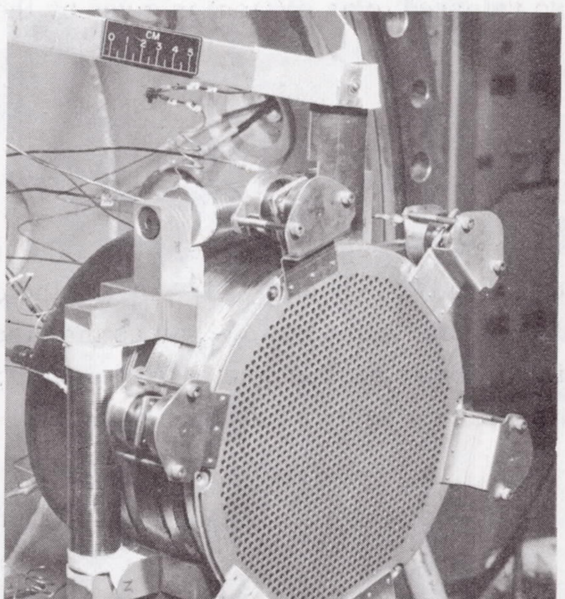


Figure 3. - Thruster 2. Discharge chamber length, 10 centimeters.

tween the two thrusters is that thruster 1 has an ion chamber length to diameter ratio of approximately 1, and thruster 2 has a length to diameter ratio of approximately 1/2. Both have tantalum ribbon filaments (cathodes) and porous tungsten vaporizers which supply the mercury propellant. The accelerator and screen grids have about 50 percent open area. The insulated solenoidal magnet coils of both thrusters were wrapped directly on the ion chamber surfaces. Thruster 1 had additional wraps at each end, which produced a fairly uniform (within 10 percent) axial field along the longitudinal axis of the ion chamber. Thruster 2 had a single-layer-wrap solenoidal coil and had some reduction of the magnetic field strength at each end of the ion chamber. Electromagnets with four pole pieces were added to both thrusters, as shown in figures 2 and 3. These pole pieces were rods or bars placed longitudinally and spaced equally on the outside of the thrusters running the entire length of the ion chambers. The pole pieces were con-

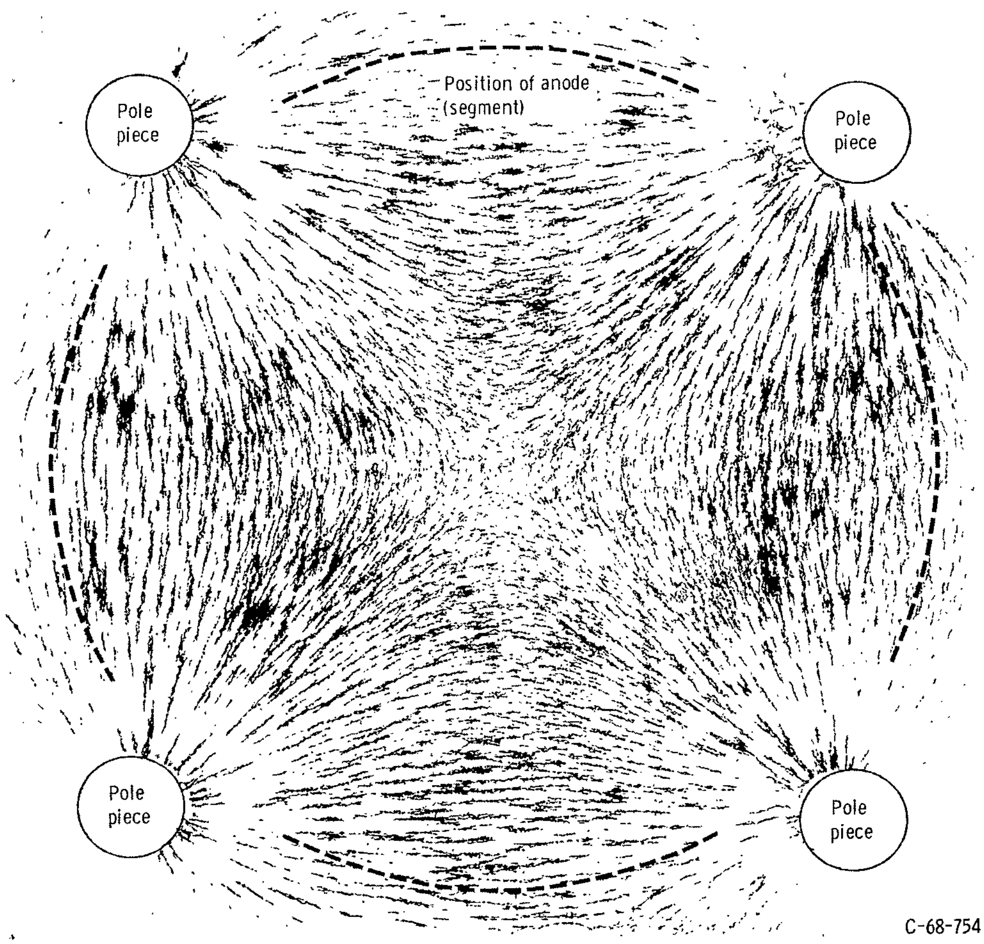


Figure 4. - Iron-filing map of cusped field showing pole pieces and segmented anode. Plane of figure is normal to thruster axis.

nected by iron rods wrapped with magnet wire. The electromagnets produced a cusp magnetic field in the ion chambers. Figure 4 is a representative iron-filling map of the cusp magnetic field in a plane normal to the thruster axis. This field could be superimposed on the axial field during thruster operation. (When referred to later, the cusp field strengths are field strengths at the midpoint of a line connecting the centers of two adjacent pole pieces.) Figure 4 shows the relative location of the pole pieces and the anode segments used in both thrusters. Figure 5 shows the segmented anode in thrus-

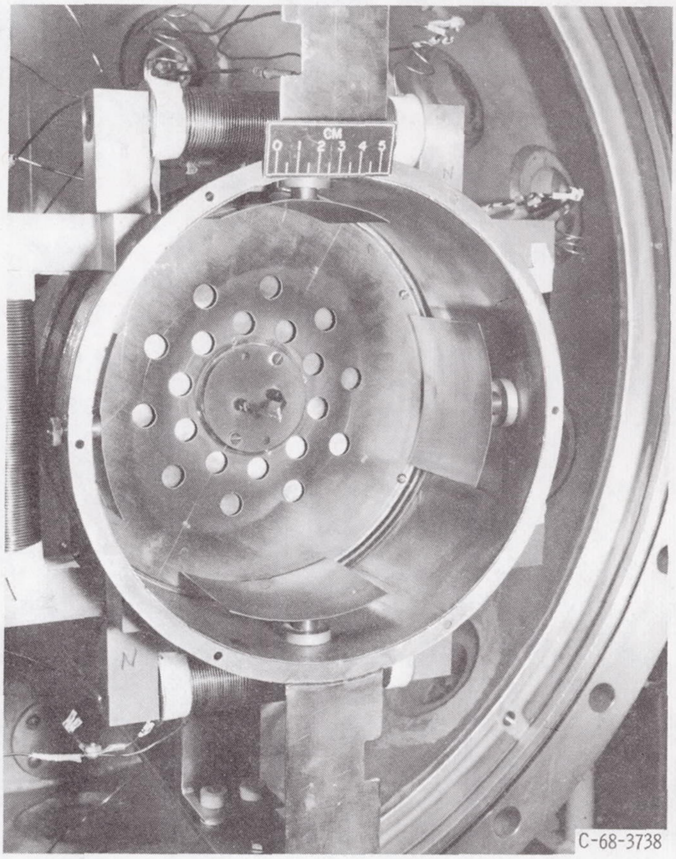


Figure 5. - Internal view of thruster 2 showing segmented anode.

ter 2. These anode segments are connected electrically in paralled during thruster operation. The purpose of using a segmented anode instead of the standard cylindrical anode is to prevent primary electrons emitted from the cathode from traveling directly along a cusp field line to the anode electrode (see fig. 4). With the anode segmented and nested in the cusp field, as shown in figure 4, primary electrons must travel across cusp field lines to reach these electrodes.

The thrusters were operated in a bell jar, approximately 1 meter in diameter, which is connected to a vacuum tank $1\frac{1}{2}$ meters in diameter and 5 meters long.

Discharge Energy Per Beam Ion

Values of discharge efficiency (eV/ion) were determined for both thrusters as a function of axial and cusp magnetic field strengths. During the tests the discharge voltage ΔV_I was held constant at 50 volts, an optimum for thrusters operating with metal filaments (ref. 5). Performance measurements were taken at a constant vaporizer temperature that corresponds to constant propellant flow rate. The beam current was also held constant during tests by adjusting the cathode heater current and hence the emission current as magnetic field changes were made. These two conditions (constant neutral flow and constant beam current), when met, yield a constant propellant utilization efficiency. Within ±10 percent, data for thruster 1 were taken at 70 percent propellant utilization efficiency, and data for thruster 2 were taken at 55 percent propellant utilization efficiency. The screen and accelerator grids were set at 2500 and -1000 volts, respectively. The grid spacing in this experiment was set at 0.2 centimeter, which gave an average electric field between grids of about 1.8 megavolts per meter. As mentioned previously, the grids have 50-percent open area. Other studies on smaller thrusters (e.g., ref. 6) have shown an improvement of about a factor of 2 in eV/ion for increased open area grids (70 percent). Thus, mainly for this reason, eV/ion values reported herein are higher than the more recent values obtained in other studies. Electrical measurements were made with conventional 3-percent panel meters.

Molybdenum Button Probe Measurements

The ion thruster exhausts a directed beam of high-velocity mercury ions. A small molybdenum disk of known area (0.32-cm diam) was placed in the beam to intercept a portion of it. The disk was placed 10 centimeters from the accelerator plates and was movable across the beam diameter. The disk was biased 22 volts negative with respect to ground to repel beam plasma electrons, and thus the disk current was about equal to the current of the intercepted beam ions. A plot of this current against radius, measured from the beam centerline, yields the beam profile.

Noise Measurements

In this experiment the current in the lead of one of the anode segments was monitored by a transformer which acted as an alternating current pickup device. In this way a measurement of plasma fluctuations or noise was obtained from the discharge chamber. Two types of noise measurements were made.

In the first measurement, the varying signal from the ion thruster was introduced into a high pass filter and then displayed on an oscilloscope. The filter was used to suppress low-frequency powerline noise (i.e., 60 Hz and its harmonics) from the signal. The noise from the discharge chamber was in the kilohertz range, and the filter was set to pass this signal. The signal was measured for peak-to-peak strength from its height on the oscilloscope and corrected for the transformer gain settings. These data (noise signal strength) were measured as a function of axial and cusp magnetic field strengths.

In the second measurement, the filter was not used; instead, the signal was introduced directly into an oscilloscope fitted with a frequency spectrum analyzer. The combination of frequency spectrum analyzer and oscilloscope was used to display noise strength against frequency directly. The gain settings remained unchanged throughout the measurements. Photographs of the frequency spectrum display were taken from the oscilloscope for different axial and cusp field strengths.

RESULTS

Performance and Noise Study of Thruster 1

One method of comparing the performance of different ion thruster configurations is to determine the discharge efficiency (eV/ion) of each. Curves of eV/ion as a

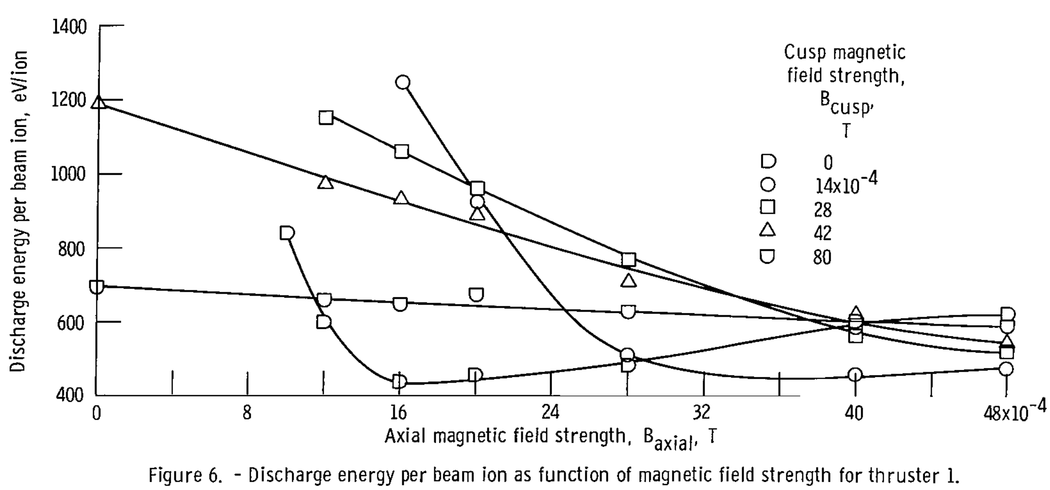


Figure 6. - Discharge energy per beam ion as function of magnetic field strength for thruster 1.

function of axial magnetic field strength for thruster 1 are shown in figure 6. Each curve represents data for a constant value of cusp magnetic field strength which was superimposed on the axial magnetic field. The curve for zero cusp field has a minimum discharge loss at an axial magnetic field strength (the critical field strength) of 1.6 milliteslas (16 gauss). Beyond this point the discharge was considered to be turbulent or anomalous because, according to classical theory, the performance should not deteriorate with increased magnetic field strength. Noise measurements (shown subsequently), as well as the calculation of reference 2, further confirm that this critical magnetic field strength is correlated with the onset of turbulence or anomalous behavior. Similar performance was noted in reference 4 for the Penning-type discharge device. Figure 6 shows that the addition of low cusp fields (e.g., 1.4 mT) causes a significant increase in discharge power per beam ion in the low axial field region. This is probably due to the introduction of a new magnetic field direction which can couple with the plasma electric fields to reduce particle containment. This loss may be due to the Hall effect, in which case it should be reduced by increasing the total magnetic field strength. As shown in figure 6, in the low axial field region, either an increase of cusp field beyond 1.4 milliteslas or an increase in axial field strength reduces the discharge power per beam ion. Figure 6 also shows that application of a cusp field strength of 1.4 milliteslas to thruster 1 yielded a curve with a minimum at a higher axial magnetic field strength than the curve with no cusp field. The critical magnetic field (boundary between classical and anomalous behavior) in this case was about twice that of the thruster with axial field alone. The minimum eV/ion was, however, about the same in both cases. Although no major improvement in discharge performance was achieved, the thruster did perform slightly better at axial fields greater than 3 milliteslas when a 1.4-millitesla cusp field was applied

For a cusp field of 28 milliteslas the curve approached the best discharge efficiency of the prior two cases, yet did not show a minimum within the range of axial magnetic field strength studied. Further increases in the cusp magnetic field strength also produced curves that approached the lowest eV/ion of the first two configurations. A new result was noted when a cusp field strength greater than 4.2 milliteslas was applied. Above this value the thruster operated relatively well with a cusp magnetic field only (i. e., at zero values of axial field strength on fig. 6). This led to a further exploration of performance with only a cusp field. The results are shown in figure 7. A discharge energy of 690 eV/ion was required for cusp-only operation at 8 milliteslas which was the limit of available cusp field strength for thruster 1 due to saturation of the iron in the cusp electromagnet. In an effort to eliminate this saturation problem, thruster 2 was built with higher cusp field capabilities and a shorter ion chamber (and hence shorter cusp pole piece) than thruster 1.

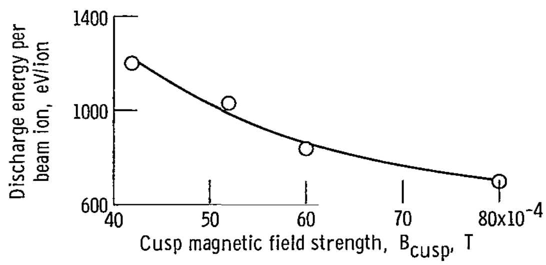


Figure 7. - Discharge energy per beam ion as function of cusp field strength for thruster 1.

In thruster 1 a rapid rise in intensity of plasma fluctuations occurred in conjunction with the anomalous diffusion phenomenon. These fluctuations were monitored as a plasma noise signal from the discharge which was displayed on an oscilloscope. Measurements of the peak-to-peak signal strength were taken as described in the measurements section of this report. Relative plasma noise intensities are shown in figure 8 for various combinations of axial and cusp magnetic fields. Note that for the axial-only curve there is a sharp rise in noise level beyond the 1.6-millitesla value. This value corresponded to the minimum eV/ion point in figure 6 was in agreement with a calculated value (ref. 2) that predicted the critical field for the onset of anomalous diffusion. Consequently, the increase in noise level beyond 1.6 milliteslas is attributed to the onset of anomalous diffusion. This agrees with the interpretation in

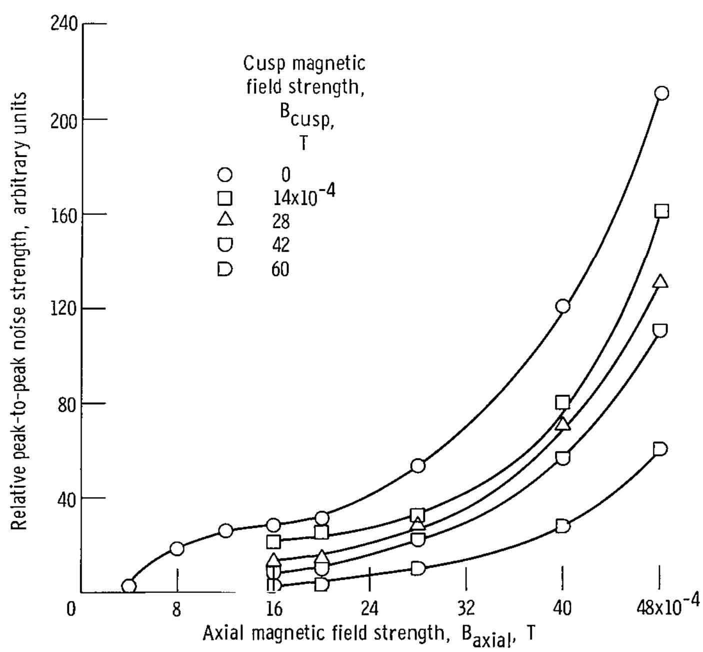


Figure 8. - Noise study for thruster 1.

reference 4, where similar noise measurements were reported for a Penning-type discharge. In that study an onset of noise corresponded to an onset of anomalous diffusion, and a suppresion of noise occurred with a suppression of anomalous diffusion.

Figure 8 shows that a marked suppression of noise occurred with the addition of cusp magnetic field. It was further observed during the course of measurements (but not shown in fig. 8) that the thruster operating with cusp field only was essentially noiseless. The magnitude of cusp field required to suppress anomalous diffusion could not be determined from figure 8 because only one critical field value (a boundary between classical and anomalous behavior) was found for the combined field application (see fig. 6). This was for the 1.4-millitesla cusp field and occured at an axial field of 3.2 milliteslas. In figure 8 this point occurs on a rising portion of the 1.4 millitesla, and the noise level is about 42 units compared with 28 units for the critical field with axial field only. No trend (critical field against noise level) can be established from the data. However, it is apparent from figure 8 that, for a given axial field strength, application of a cusp field (up to a maximum of 6 mT) does suppress the noise level. This permits relatively noise-free operation (at sufficient cusp field strengths) at higher axial field values, up to a maximum of 4.8 milliteslas. However, even though the axial field strength of the combinations could be increased in this experiment from 1.6 to 4.8 milliteslas and the cusp field strength from 1.4 to 8.0 milliteslas, only minor improvements in discharge chamber performance were found.

Performance and Noise Study of Thruster 2

Thruster 2 was used primarily to determine the lowest level of discharge losses from a cusp-only field, as compared with use of an axial field only, for the same thruster. At a cusp field strength greater than 6.4 milliteslas, the discharge unexpectedly quenched. This limited operation to below (6.4 milliteslas even though a larger field strength was available. Figure 9 shows eV/ion data of thruster 2 plotted in the same manner as for thruster 1 in figure 6. In comparison with figure 6, there is less indication of suppression of anomalous diffusion as shown by the proximity of the critical field points of each combined field curve to the critical field point of axial-only operation. The critical axial-only field was lower for this thruster. Figure 10 shows the range of values of eV/ion against cusp magnetic field strength with no axial field. Operation at 6.4 millitesla cusp field strength in thruster 2 (cusp-field-only operation) was an improvement over similar operation (for a cusp-field-only configuration) in thruster 1, as shown from a comparison of figures 7 and 10.

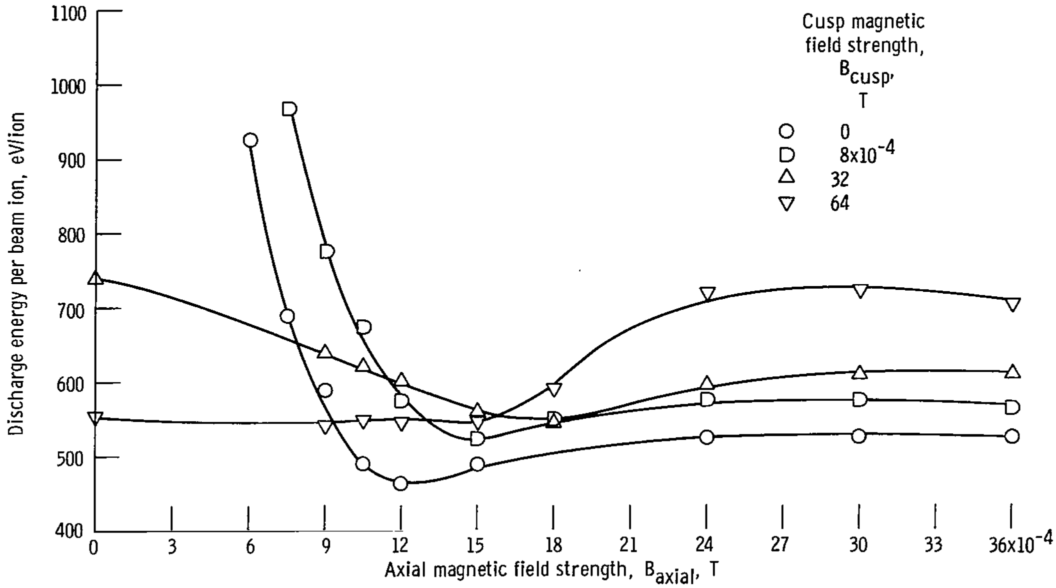


Figure 9. - Discharge energy per beam ion as function of magnetic field strength for thruster 2.

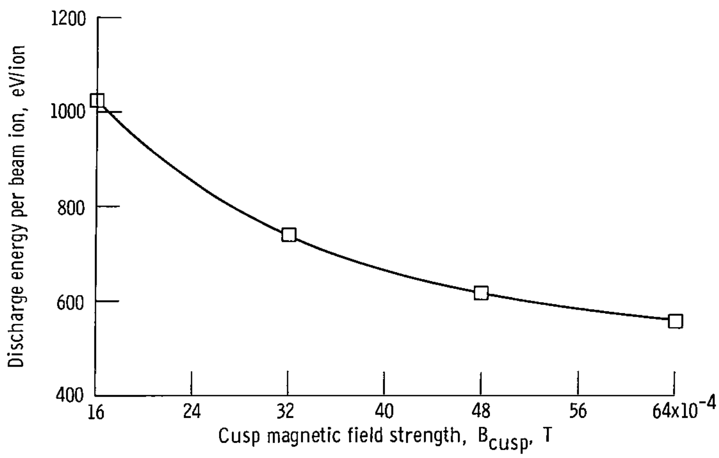
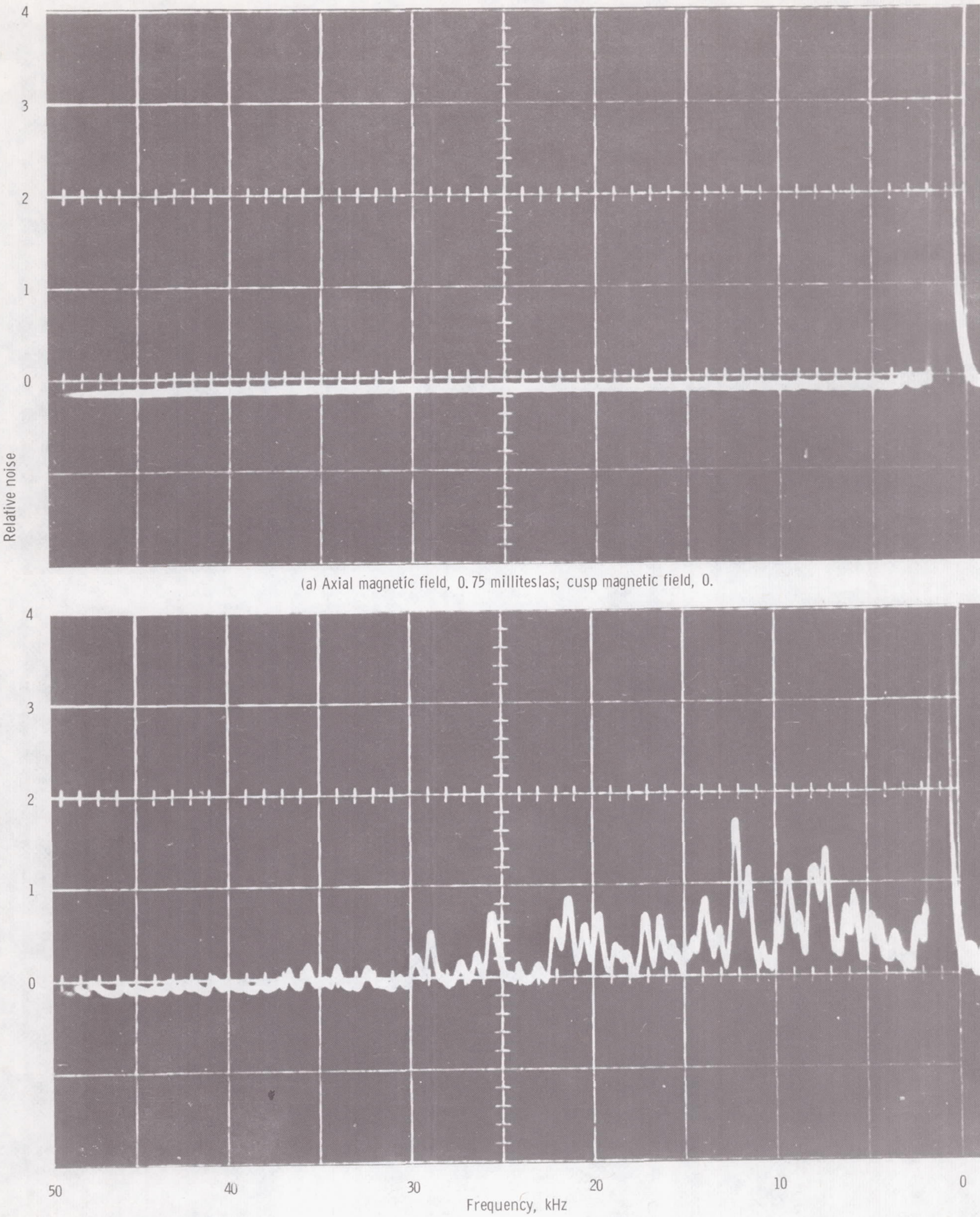


Figure 10. - Discharge energy per beam ion as function of cusp field strength for thruster 2.

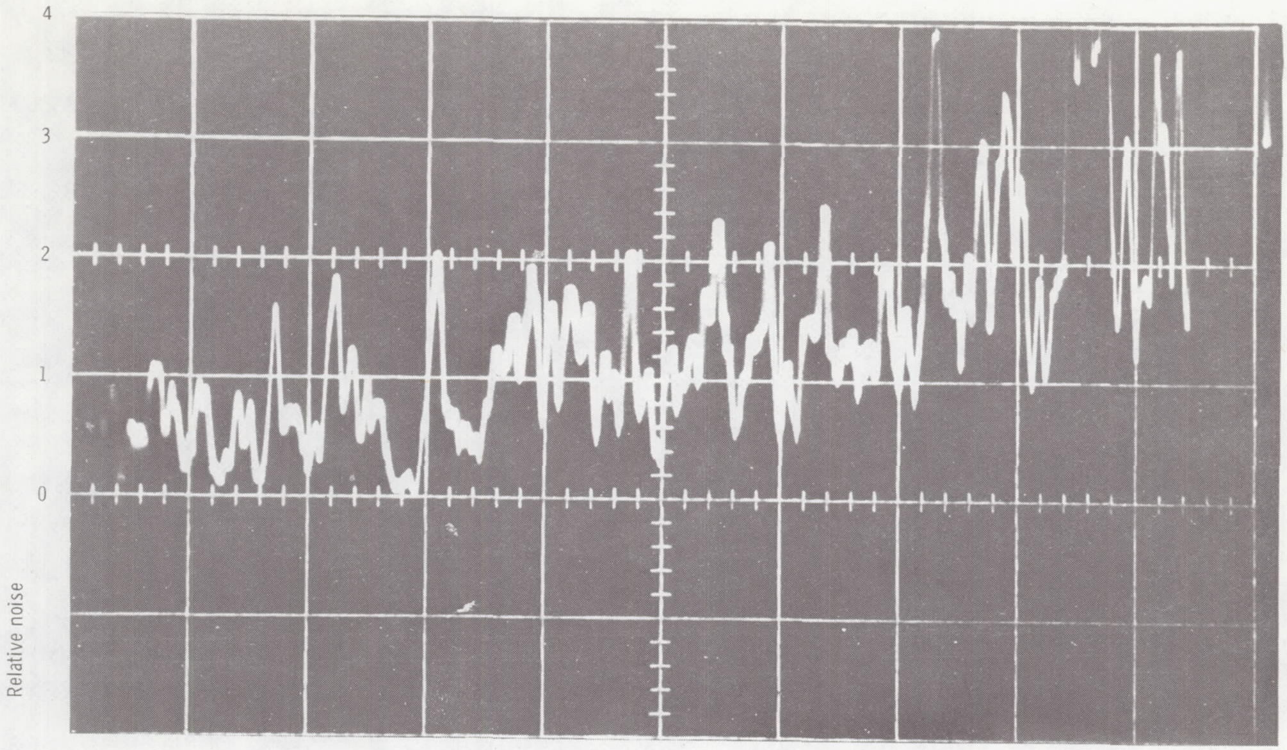
With thruster 2 operating, noise measurements were taken with a frequency spectrum analyzer. Figure 11(a) to (d) are for axial field only; the remaining parts of figure 11 are for cusp-only and combined fields. Figure 11(a) shows the signal when the thruster was operating with axial field alone but below the critical magnetic field strength. No noise is observed. The sharp peak at the right is generated by the spectrum analyzer itself. The spectrum from left to right covers a range from 50 to 0 kilohertz, a typical range of frequencies for the type of anomalous diffusion usually found in bombardment thrusters. Figure 11(b) shows the onset of noise when the thruster was



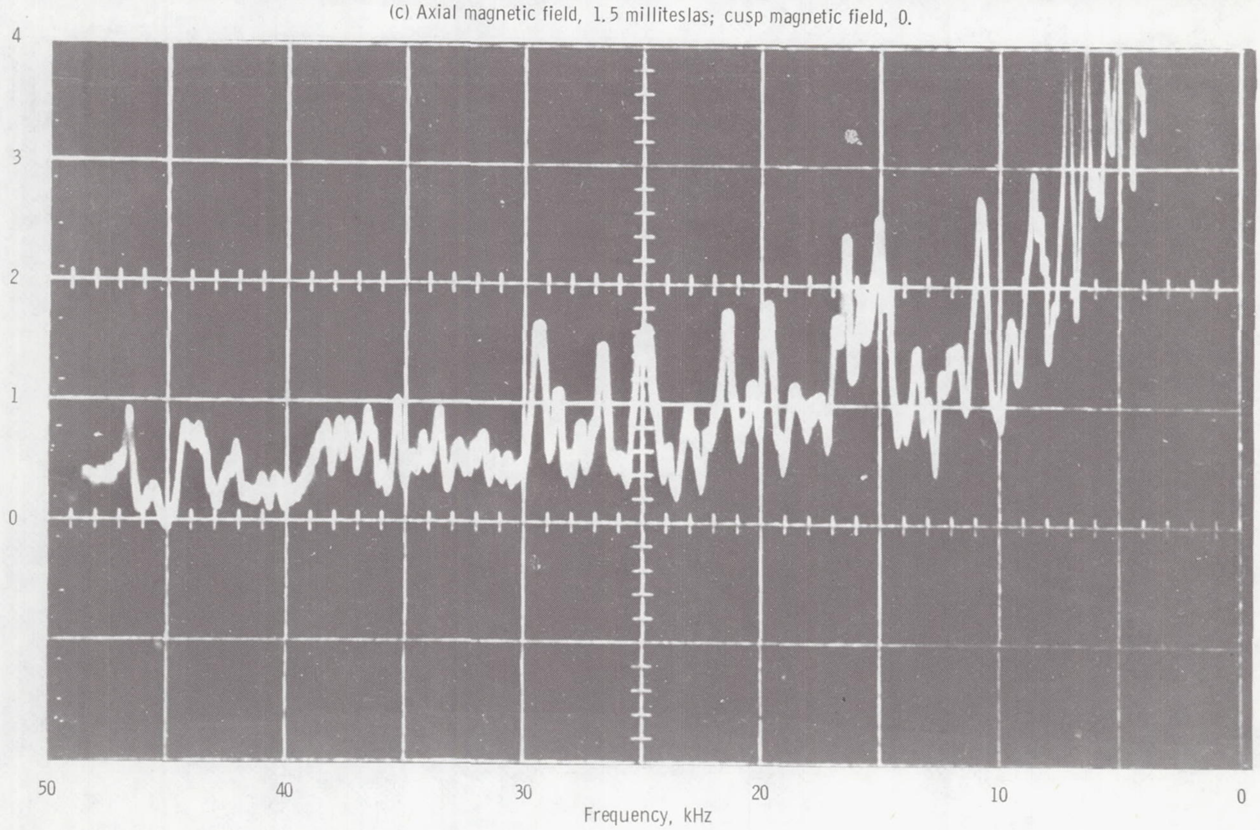
(a) Axial magnetic field, 0.75 milliteslas; cusp magnetic field, 0.

(b) Axial magnetic field, 1.2 milliteslas; cusp magnetic field, 0.

Figure 11. - Noise traces for thruster 2.

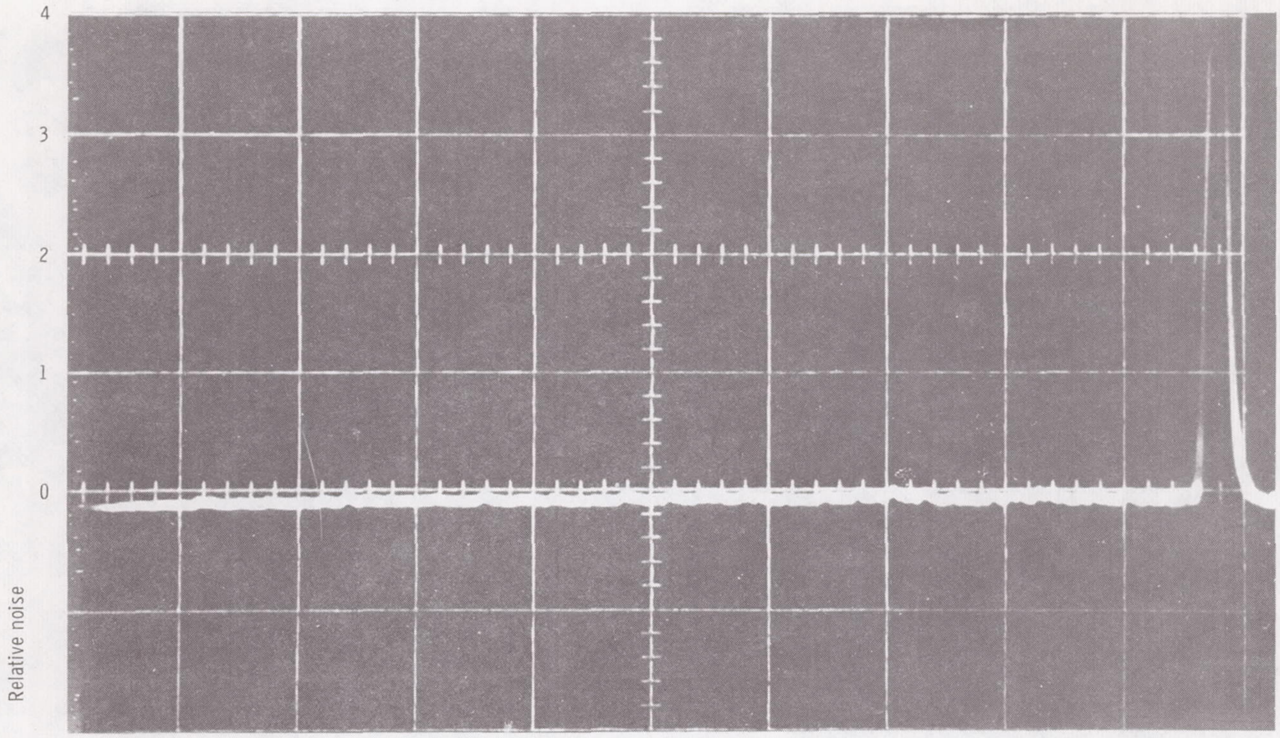


(c) Axial magnetic field, 1.5 milliteslas; cusp magnetic field, 0.

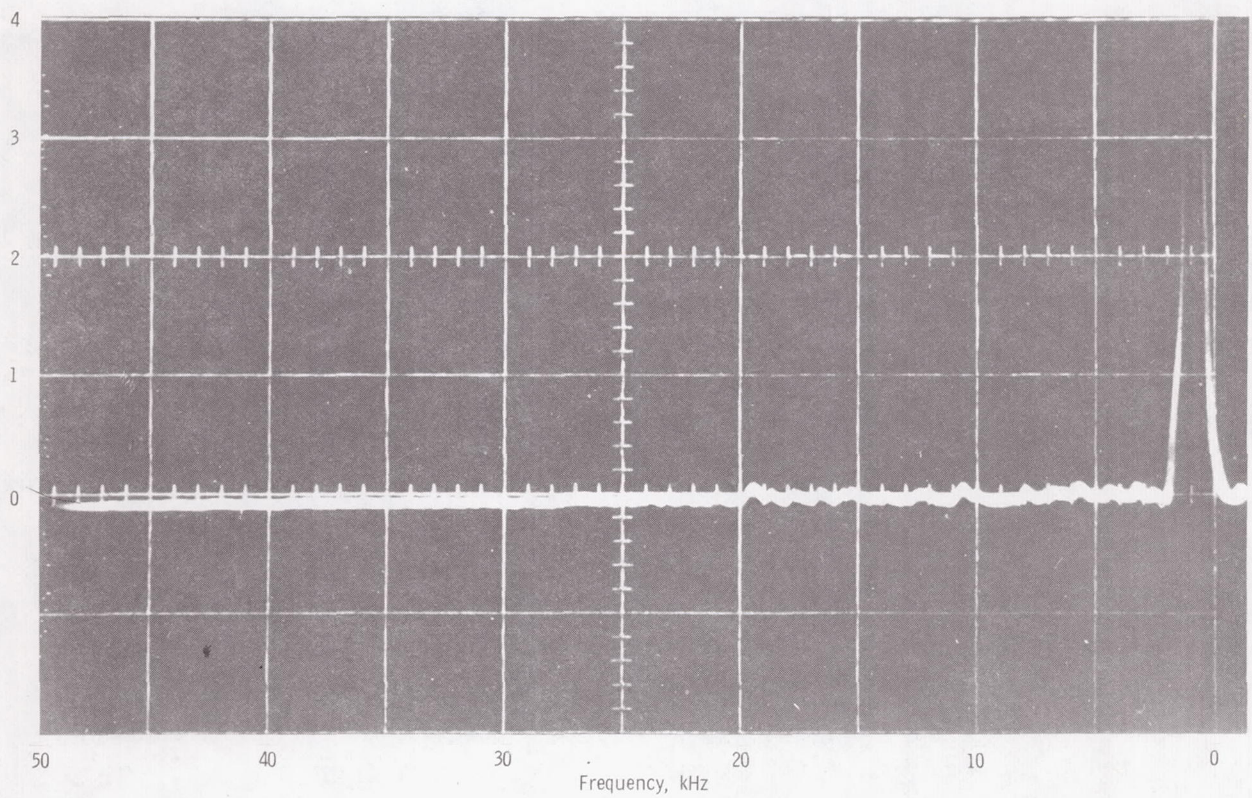


(d) Axial magnetic field, 3 milliteslas; cusp magnetic field, 0.

Figure 11. - Continued.

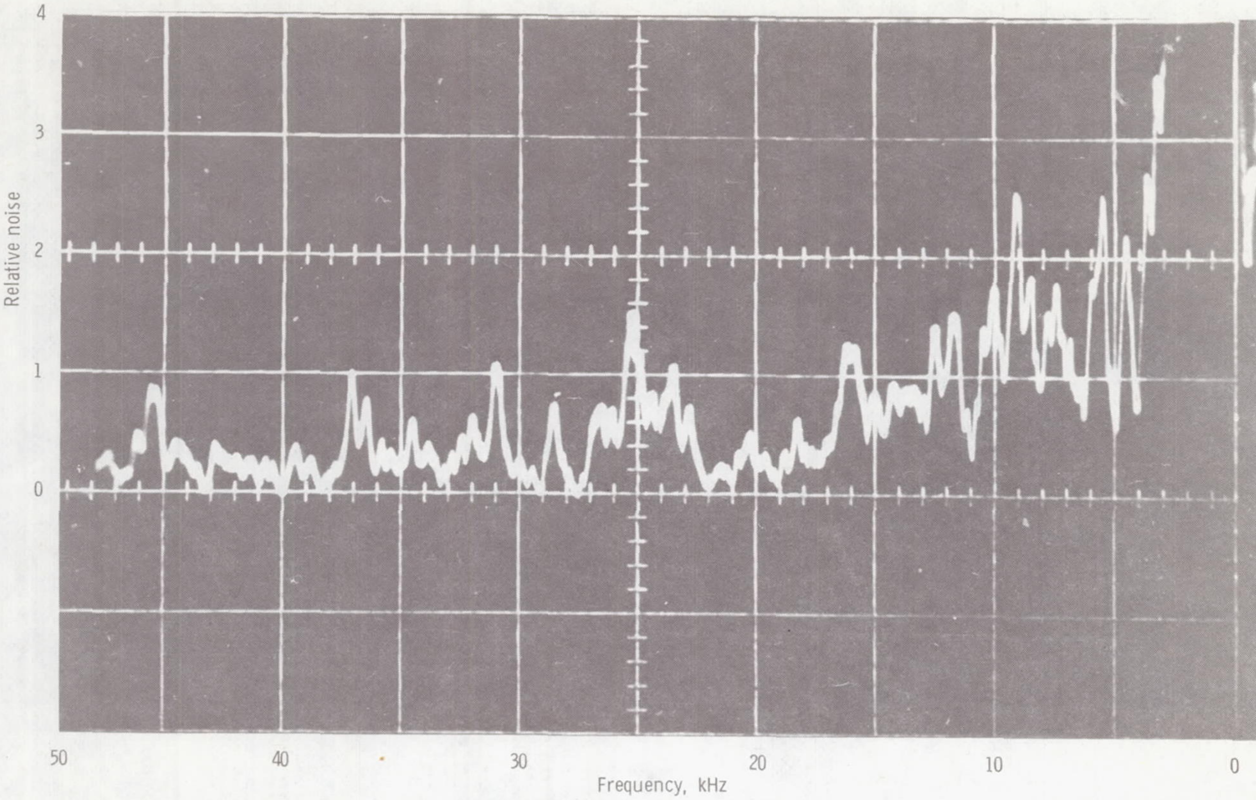


(e) Axial magnetic field, 0; cusp magnetic field, 6.4 milliteslas.



(f) Axial magnetic field, 1.5 milliteslas; cusp magnetic field, 3.2 milliteslas.

Figure 11. - Continued.



(g) Axial magnetic field, 3 milliteslas; cusp magnetic field, 6.4 milliteslas.

Figure 11. - Concluded.

operating at the critical magnetic field (axial-only operation). The effect of increasing the axial field strength to 1.5 milliteslas is shown in figure 11(c). In the operation corresponding to figure 11(d), an axial field strength of 3 milliteslas was reached, and the noise signal peaked below 6 kilohertz. The noise signal was strong enough in this range (below 5 kHz) so that the trace went off scale. When thruster 2 was operated on cusp field only (at a strength just below discharge quenching), the noise trace shown in figure 11(e) was taken. The operation was relatively noiseless, indicating the absence of turbulence or anomalous diffusion in operation with cusp magnetic field only. The thruster was next operated at an axial field strength slightly above the critical magnetic field and also with a cusp field. Figure 11(f) shows the almost complete lack of noise, and indicates the suppression of anomalous diffusion (compare figs. 11(c) and (f)). In figure 11(g) a large amount of noise was obtained for the thruster operating at high axial and high cusp field strengths. This high noise level indicates that it was not possible to suppress the anomalous diffusion in this thruster at high axial field strengths. This is in agreement with critical field values for the eV/ion curves of figure 9.

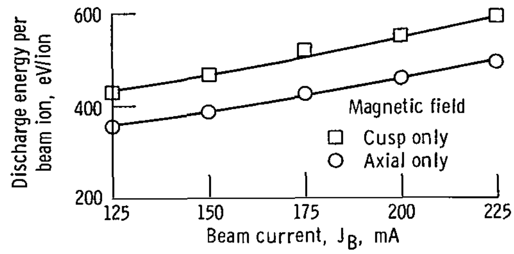


Figure 12. - Discharge energy per beam ion as function of beam current for thruster 2. Total propellant flow, 286 milliamperes equivalent mercury ion current.

A plot of discharge efficiency (eV/ion) against beam current for constant propellant flow in thruster 2 is shown in figure 12. The two sets of data points represent the best operation for axial-field-only and cusp-field-only configurations. The data show that the variation of eV/ion with propellant utilization is about the same for the two magnetic field configurations.

Another measurement made in this study was the beam profile for thruster 2 operating on axial-only and cusp-only magnetic configurations. Figure 13 shows the beam profiles obtained from molybdenum disk swept across the beam, 10 centimeters from the thruster grids. No significant difference in profiles was discovered for these two very different magnetic field configurations. Because the measurements were made close to the grid system, the beam profiles indicate that the internal plasma density distribution was similar for the two field types.

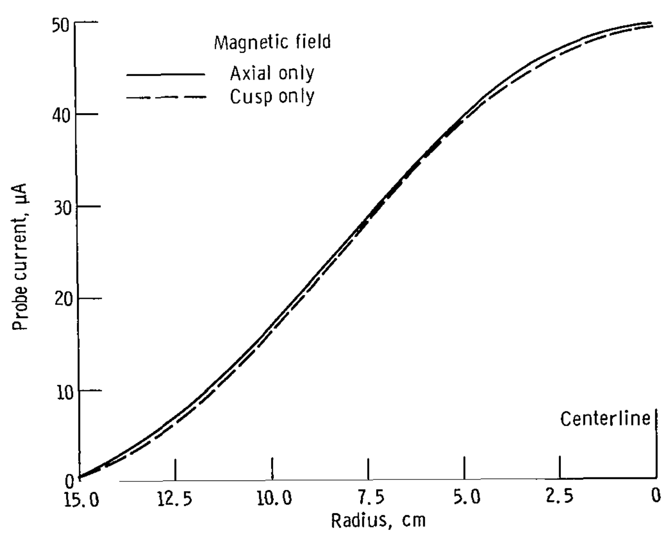


Figure 13. - Exhaust beam profile for thruster 2.

DISCUSSION

The minimum discharge energy loss (eV/ion)measured in this study corresponded to operation at the critical field strength with axial field only. With only the cusp field and with combination of axial and cusp field, the discharge efficiencies approached this minimum eV/ion. In some cases during operation with a combination of axial and cusp magnetic field, a new and higher critical field strength was found. In other cases the minimum eV/ion was approached, and it seemed possible that a new critical field strength would be reached outside the range of measurement. In the cusp-only configuration of thruster 2 the minimum eV/ion was approached, but the discharge was found to quench.

The reduction of noise corresponding to anomalous diffusion as well as the appearance of higher critical field strengths indicated that the anomalous diffusion phenomenon was suppressed (at least over a range of axial field strengths). The lack of noise in the thruster operating with cusp magnetic field only indicates freedom from turbulence or anomalous diffusion in this mode.

The results of this experiment with axial and cusp configurations seem to indicate that an axial field strength strong enough to initiate anomalous diffusion is also strong enough to produce the ideal condition as described in the INTRODUCTION. This condition is simply that the magnetic field strength is sufficient to cause the primary electrons to dissipate most of their directed energy in the plasma so that only minimum amount of energy remains when they reach the anode electrode. Satisfaction of this condition would explain why suppression of anomalous diffusion with the cusp field failed to reduce ion production cost.

CONCLUDING REMARKS

The performance of two electron-bombardment thrusters of two different lengths was investigated with axial magnetic field, combination axial and cusp field, and cusp field only. Discharge chamber performance and discharge noise measurements were obtained. The performance of the thrusters was presumed to be imparied by anomalous diffusion. Were this the case, the suppression of this process by the application of a stabilizing magnetic field (a cusp field in this study) would yield lower beam ion production costs. This improvement in performance was not realized.

The best performance was found for the thrusters running with the conventional axial field only and at the critical magnetic field strength. Application of a relatively small cusp field strength (in addition to the critical axial field strength) led to a large increase in discharge chamber losses. The discharge losses could be lowered by an increase in either cusp or axial field strength and made to approach the best performance by sufficient field strength. This best performance was also approached with cusp-only operation.

Higher critical field strengths as well as reduced noise levels were observed for the combination axial and cusp field operation. Cusp-only configuration operated noise free. The noise spectra of thruster 2 was particularly interesting and consistent with the interpretation of the critical magnetic field as the boundary between classical and anomalous diffusion. These results led to the conclusion that anomalous diffusion was suppressed in this investigation. The lack of performance-improvement with suppression of anomalous diffusion indicates that the critical axial field strength was already sufficiently strong to achieve its major purpose of causing primary electrons to lose most of their energy within the plasma volume.

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National Aeronautics and Space Administration,
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