Electron Backstreaming Mitigation via a Magnetic Grid*†

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IEPC-01-91

Electron backstreaming due to accelerator grid hole enlargement has been identified as a failure mechanism that will limit ion thruster service lifetime. Over extended periods of time as accelerator grid apertures enlarge due to erosion, ion thrusters are required to operate at increasingly higher accelerator grid voltages in order to prevent electron backstreaming. These higher voltages give rise to higher grid erosion rates, which in turn accelerates aperture enlargement. Presented here is an approach to mitigate the backflow of electrons into the engine by using a transverse magnetic field.

Nomenclature

$\mathbf{B}$ = Magnetic field
$D_\perp$ = Cross-field electron diffusion coefficient
D_e = Field free electron diffusion coefficient
e = Elementary charge of an electron
E_s = Electric Field
J_{beam} = Ion beam current
J_{limit} = Measured ion beam current at backstreaming limit
k = Boltzmann's constant
m_e = Electron mobility
m = Mass of electron
v_e = Electron collision frequency
n_e = Electron number density
w = Electron cyclotron frequency
r = Displacement normal to field line direction
T_e = Electron temperature
$|V_a|$ = Absolute value of accelerator grid voltage

*Presented as Paper IEPC-01-91 at the 27th International Electric Propulsion Conference, Pasadena, CA 15-19 October, 2001. †This paper is declared a work of the U.S. Government and is not subject to copyright protection in the United States.

Introduction

Aggressive deep-space mission requirements can be satisfied by the use of high specific impulse systems such as ion thrusters. Ion thrusters are a proven technology for deep space missions as demonstrated in Deep Space 1 (DS1) mission.[1] For example, the DS1 ion engine has thrusted for over 13,000 hours and has processed over 60 kg of xenon to date.[2] The DS1 flight spare ion engine has been life-tested for over 18,000 hours and has consumed over 150 kg of xenon to date.[2] In order to satisfy mission requirements for more demanding missions such as Titan explorer, Neptune Orbiter or Interstellar Precursor, the ion thruster must provide a significantly longer total impulse capability. To meet long operation time and high propellant throughput requirements, thruster lifetime becomes paramount. In general, potential ion thruster failure mechanisms associated with long duration thrusting can be grouped into four areas:[3,4] 1.) Ion optics failure, 2.) Discharge cathode failure 3.)

Neutralizer failure, and 4.) Electron backstreaming due to accelerator grid aperture enlargement brought on by accelerator grid erosion. Ion optics failure modes include accelerator grid structural failure due to erosion from direct ion impingement or charge exchange ion flux, grid shorting due to the formation of large, conducting flakes, and screen grid structural failure due to erosion from bombarding discharge ions. Cathode failures modes include orifice plate erosion and cathode heater failure. Neutralizer failure modes include cathode to keeper shorts and cathode erosion due to plume mode operation. This paper will focus on *electron backstreaming*, which occurs when the potential at the center of an accelerator grid aperture is insufficient to prevent the backflow of electrons into the ion thruster. The likelihood of this occurring depends on ion source operation time, plasma density, and grid voltages, as accelerator apertures enlarge due to erosion processes. Once the electrons enter the gap between the high voltage screen and accelerator grid, they are accelerated to the energies approximately equal to the beam power supply voltage. This energetic electron beam (typically higher than 1 kV) can damage not only the ion source discharge cathode assembly, but also any of the discharge surfaces upstream of the ion acceleration optics that the electrons happen to impact. Indeed, past backstreaming studies have shown that near the backstreaming limit there is a rather sharp rise in temperature at structures such as the cathode keeper electrode.[5] In this respect, operation at accelerator grid voltages near the backstreaming limit is avoided.

Generally speaking, electron backstreaming is prevented by operating the accelerator grid at a negative voltage to assure a sufficiently negative aperture center potential. This approach can provide the necessary margin assuming an expected aperture enlargement. Operation at very negative accelerator grid voltages (required to provide the necessary margin), however, enhances charge-exchange ion erosion. In this respect, the presence of the negative voltage, which is supposed to prevent electron backstreaming, actually enhances another problem--erosion of the accelerator grid (failure mode 1).

The focus of this work is that of mitigation of the electron backstreaming problem by using a magnetic field. The presence of a magnetic field oriented perpendicular to the thruster axis can significantly reduce the magnitude of the backflowing electron current by severely reducing the electron diffusion coefficient. Negative ion sources utilize this principle to reduce fraction of electrons in the negative ion beam.[6-10] The focus of these efforts has been on the attenuation of electron current in the negative ion beam by placing the transverse magnetic field upstream of the extraction electrodes. This arrangement restricts electron flow to the negative ion extraction electrodes. In the case of positive ion sources such as ion thrusters, the approach taken in the work presented here is to apply the transverse field *downstream* of the ion extraction system so as to prevent electrons from flowing back into the source. It was found in the work presented here that the magnetic field also *reduces the threshold accelerator grid voltage at which electron backstreaming occurs*. In this respect, the applied transverse magnetic field provides two mechanisms for *electron backstreaming mitigation*: 1) electron current attenuation and 2) backstreaming limit voltage shift. From an engineering standpoint, the shift in the electron backstreaming voltage limit produced by the presence of the transverse magnetic field is very important. This shift provides operating margin and thereby reduces the magnitude of negative voltage that must be placed on the accelerator grid. Such a reduction reduces accelerator grid erosion rates.

Conceptual Basis

In general, the diffusion of electrons across a magnetic field can be described:[11]

$$J_e = -e \cdot \mu_e \cdot n_e \cdot E_s - e \cdot D_\perp \cdot \frac{dn_e}{dr} \qquad (1)$$

Under conditions where electron backstreaming occurs, the electric field opposing electron backflow is small and thus the second term in Equation (1) can dominate and thus drive the electrons into the gap between the accelerator grid and the screen electrode. The cross-field diffusion coefficient in the limit of zero magnetic field depends on collision frequency and electron temperature:

$$D_e = \frac{kT_e}{m \cdot \nu_e} \qquad (2)$$

In such a case, diffusion into the engine follows Fick's law. As the transverse magnetic field increases, the transverse diffusion coefficient, classically becomes:

$$D_{\perp} = \frac{D_e}{\left[1+\left(\frac{w^2}{n_e{}^2}\right)\right]} \qquad (3)$$

Here, in the limit of large magnetic field, the transverse diffusion coefficient scales as $D_{\perp} \propto \frac{1}{B^2}$. In this respect, a transverse magnetic field can significantly reduce the back-flux of electrons into the thruster. The primary basis of this research hinges on the ability of a magnetic field to modify electron transport.

The imposed magnetic field should also induce a shift in the electron backstreaming voltage limit. Under normal thruster conditions, low energy electrons are prevented from entering the engine due to repulsive center potentials at the accelerator grid. The more energetic electrons can backflow, provided they can surmount the energy barrier. Therefore, the primary electrons should be the first species to backstream because they are the first to have the energy to cross the barrier as the accelerator grid potential is reduced. The imposition of a transverse magnetic field, however, can be used to shut off the backflow of this energetic component of electron current. Therefore, in the presence of the transverse magnetic field, the electron backstreaming voltage limit should occur at a less negative potential. The requirement for the reduced backstreaming voltage limit is that the center potential of the accelerator aperture is sufficiently negative to repel thermal electrons which would otherwise diffuse across magnetic field lines by scattering due potential fluctuations and instablitilites.[12,13]

The shift in the backstreaming limit should be calculable. An ion optics code can be used to determine under what conditions the center potential of accelerator grid is negative enough to prevent the backflow of thermal electrons. Provided the transverse magnetic field is sufficiently large, this accelerator grid voltage represents the lower limit at which the thruster can safely operate without electron backstreaming. The shift in the backstreaming limit should be the difference between this new accelerator grid voltage and backstreaming limit at **B**=0 T.

There is a limit, however, as to how high the magnetic field can be practically increased for electron backstreaming mitigation. Though significant ion beam deflection can occur at very large field strengths (~Tesla range), the likely issue that will place an upper limit on the magnetic for this application is associated with magnetic field induced sheath effects on upstream surface of screen grid. The likelihood of the leakage of magnetic field lines generated downstream of the accelerator grid into the discharge chamber increases with increasing magnetic field intensity. The leakage of field lines into the discharge chamber effects electron motion near the sheath at the screen. This, in turn, influences ion drift near the screen as well, thereby affecting the effective screen grid transparency.

Experimental Set-up

The magnetic grid experiments took place at the NASA Glenn Research Center Vacuum Facility 11. A photograph of the facility is shown in Figure 1. The aluminum facility is approximately 2.2 m in diameter and 7.9 m in length. The pumping train includes a two-stage blower system backed by a roughing pump, a turbomolcular pump, and seven helium cryopumps. The approximate pumping speed was 110,000 l/s on xenon at 1.3×10^{-4} Pa. The nominal base pressure was 1.3×10^{-5} Pa.

A 30 cm NSTAR-type ion thruster with a modified ion optics system was used in this investigation.[14] Details regarding the 30-cm engine used in this test, the power console, and the xenon feed system can be found elsewhere.[14] Small scale, 45 aperture gridlets were used in this investigation to extract a beam. As can be seen in Figure 2, the thruster's exit plane was masked down with a set of dished domes to accommodate the ion extraction gridlets. The screen gridlet consisted of a 0.762 mm thick molybdenum plate while the accelerator grid was fabricated from 1 mm thick SAE 1050 steel plate. The 1050 steel was selected to increase the magnitude imposed transverse magnetic field. The screen electrode contained apertures 1.91 mm in diameter while the accelerator grid apertures were 1.13 mm in diameter. The apertures were arranged in a 9 x 5 rectangular array that was centered about the thruster axis. The lateral center to center spacing between apertures on a given row was approximately 3.0 mm. The aperture center to center spacing between apertures in adjacent rows, however, was approximately 5.0 mm. A 0.66 mm gap between the screen and accelerator grid was maintained using a mica washer.

The transverse magnetic field was generated by copper conductors that ran between each aperture row. The transverse magnetic field in a plane just above the alumina tubing that houses the copper conductors could be varied between 0 T and approximately 0.003 T as determined by Gauss-meter measurements. The outer diameter of the alumina tubing that housed the copper conductors used in this investigation was 2.66 mm. A total of six straight conductors were used, each of which was located next to an adjacent row of apertures (see Figure 2). As mentioned earlier, the field generated downstream of the accelerator grid by these current conductors was enhanced by the presence of the mild steel accelerator electrode to which the conductors were affixed. A pictorial depiction of this scheme is illustrated in Figure 3a. As shown in the Figure 3a., the current flowing in the same direction gives rise to closed magnetic flux contours across the face of the optics. Figure 3b. shows computer simulated magnetic field contours generated by 6 straight conductors operating at 12 A each on a mild steel plate. This geometry and dimensions used in the simulation are similar to the hardware configuration used in this test. As can be seen in this magnetic contour plot, the straight conductor electromagnets generate a fairly uniform, transverse magnetic field downstream of the optics.

The approach, which entails the use of electromagnets, was chosen for this investigation not only for its ability to generate a uniform magnetic field, but also the ability to vary in-situ the magnetic field during a test. It should be pointed out that the transverse magnetic field could also be generated with a permanent magnetic circuit. Though the permanent magnet approach is attractive from a simplicity standpoint, it, however, reduces experimental flexibility because the magnetic field in this configuration is fixed and therefore cannot be changed during a test. Even so, a scheme that implements a permanent magnet based approach was also tested.

In order to determine if the applied magnetic field had an effect on the ion beam generated, a Faraday probe was swept across the plume using a two axis motion control system. The Faraday probe used in this test was a 5.58 mm diameter planar molybdenum disk biased at –28 V with respect to tank ground. This probe was swept across the plume at a distance of 70 mm downstream of the optics.

Experimental Approach

In general, electron backstreaming measurements are made by reducing the negative voltage of the accelerator grid until the center potentials at accelerator grid apertures are insufficient to prevent electron backflow. When this occurs, the measured ion beam current begins to increase exponentially. (As measured by the beam power supply, a backstreaming electron entering the discharge chamber is equivalent to an ion leaving the ion source.) The electron backstreaming limit was defined as the accelerator grid voltage where further decreases in its absolute value will give rise to a measurable increase in the apparent ion current. In this work, the backstreaming voltage limit was determined by locating the accelerator grid potential at which further voltage reductions would give rise to a 1% increase in beam current. The location of the 1% increase was approximately near the turning point or “knee” of the backstreaming current-voltage characteristic. At this voltage, the apparent ion current switches from slowly varying function of the accelerator potential to an exponentially increasing function of the accelerator potential. It should be pointed out that thermocouple evidence suggests that the backstreaming voltage limit may actually occur somewhat earlier than as indicated by this approach. Sharp rises in cathode-keeper temperature, presumably arising from electron beam heating of the keeper, have been measured at voltages 5 to 10 V before the knee.[5] In this respect, the measured apparent ion current at voltages at and somewhat before the “knee” of the backstreaming voltage characteristic likely represents a sum of exiting ions and backstreaming electrons.

Results and Discussion

Screen Grid Transparency

It was found that as compared to the B=0 T case, as the magnetic field was increased from 0 T to approximately 0.0030 T, the measured ion beam current decreased between 7% and 10%. The accelerator grid impingement current however did not increase, suggesting that the magnetic field did not influence the motion of the ions. The reductions in ion current are likely attributable to the leakage of magnetic field lines into the discharge plasma. This leakage of magnetic flux can affect the shape of the sheath on the upstream side of the screen grid as well as current flow into this sheath. Such changes can in turn affect the effective screen grid transparency. A change in transparency is likely the cause of the reduction in the measured ion beam current with increasing magnetic field strength. In order to compensate for this effect during the course of electron backstreaming voltage measurements, the discharge current was *increased* to increase the beam current to its original B=0 T value after each change in magnetic field intensity. The percent increase in the discharge current ranged from 17 % at 0.0010 T to 68% at approximately 0.0030 T. Discharge voltage did not vary in response to the discharge current changes. It is assumed that the increase in discharge current brings the sheath conditions at the screen back to those that prevail at B=0 T. In principle, the problem of field leakage can be addressed by making the accelerator grid out of a higher permeability material such as iron. Iron at 0.0020 T has a magnetic permeability of approximately 30 times that of cold rolled steel.[15] A high permeability material could be used to shield the discharge plasma from the magnetic flux leakage. It should also be pointed out that the sensitivity of the discharge plasma near the screen might also be a function of ionization efficiency. Masked-down engine operation, utilized here to accommodate the small gridlets, tends to reduce the discharge voltage and ionization efficiency at a given discharge current. It is expected that the discharge should be less sensitive to stray magnetic field effects under conditions where the ionization efficiency is higher.

Beam Profile

The transverse magnetic field, which ranged between 0 T and 0.003 T, in principle should not appreciably effect the propagation of the ion beam. At these field strengths, the ion Larmor radius at beam energies (1-2 kV) was orders of magnitude larger than the grid gap or any characteristic dimension of the apertures. In order to confirm the non-perturbative effect that the field had on the beam, Faraday sweeps were taken across the center of the rectangular array for conditions with and without the transverse magnetic field imposed. Figure 4 illustrates typical behavior observed. The profile data presented in this figure was taken at a 1.95 mA beam condition with 1250 V on the screen grid and –250 V on the accelerator grid. The Faraday sweep was taken 70 mm downstream of the optics. The low ion beam current was a consequence of reduced discharge voltage and ionization efficiency associated with masked-down engine operation. As can be seen in the figure, there is little difference in between the ion beam profiles taken at B=0 T and at B=0.0019 T when appropriate adjustments are made to the discharge current.

Apparent Ion Current Reduction at the Backstreaming Limit

In order to assess the attenuation effect of the magnetic field on electron backstreaming current, the ion beam current at the backstreaming voltage limit was measured as a function of magnetic field strength. Data for this study was acquired at a 1050 V screen grid voltage and a 1.95 mA ion beam. A representative electron backstreaming characteristic at the B=0 T condition is shown in Figure 5a. Near the backstreaming limit, the center potentials at the accelerator grid apertures are no longer negative enough to repel backflowing electrons. The electron current increases exponentially as the center potentials decrease with reductions in the accelerator voltage below the backstreaming limit. Near the backstreaming limit, the metered current was found to decrease with increasing magnetic field strength. This monotonic decrease in the measured current at the backstreaming limit is illustrated in Figure 5b. The reduction in measured current is attributed to the attenuation of backstreaming electron current. The magnetic field reduces the electron transverse diffusion coefficient and thus effectively reduces the backstreaming electron current. The reductions in the transverse diffusion coefficient with increasing magnetic field strength are expected to be classical with the diffusion coefficient scaling as $1/B^2$. In this respect, the electron current that enters the engine during electron backstreaming conditions should also vary as $1/B^2$ with increasing magnetic field strength. Indeed, under conditions where the electric field opposing electron flow is small, the behavior of the electron current can be dominated by the magnetic term in Equation (1). Figure 5c illustrates the behavior of the difference between the metered ion beam current at Va=-250 (no backstreaming) and the ion beam current at the backstreaming limit as a function of $1/B^2$. The linear behavior of the curve suggests that the ion current difference is due a reduction in backstreaming electron current, an effect which should increase with increasing magnetic field strength. If the change in ion current as illustrated in the figure is indeed due to electron current, then, backstreaming electron current at the backstreaming limit may account for a non-trivial fraction of the ion beam current.

Variations in the Electron Backstreaming Limit with Magnetic Field

The attenuation of the magnitude of the backstreaming electron current with increasing magnetic field was expected as implied by equation 1. Indeed, energetic electrons can be well controlled by the application of a transverse magnetic field.[12,13] Low energy electrons, however, tend to diffuse across magnetic field lines more readily as they can be driven by potential fluctuations and instabilities.[12,13] In this regard, the utility of using a magnetic field to completely shut off backstreaming electrons is ultimately limited by the instabilities present. In addition to the reduction in the backstreaming current at and below of the backstreaming voltage limit, a shift in the absolute value of the electron backstreaming voltage to lower values was measured. *This interesting finding suggests that the magnitude of the accelerator grid voltage can be reduced to lower voltages by the application of the transverse magnetic field, thereby giving the engine additional operating margin and lifetime.* Figure 6 shows the change in the magnitude of the electron backstreaming voltage limit as a function of magnetic field strength. The data presented in this figure were taken at a beam voltage of 1050 V and a beam current of 1.95 mA. As can be seen here, the electron backstreaming voltage limit decreases linearly with increasing transverse magnetic field strength. Also shown in this plot is the percentage reduction in the backstreaming limit with increasing magnetic field strength. As can be seen from the figure, the backstreaming voltage limit was reduced by over 20 % at approximately 0.0030 T. Using the linear fit of this data for extrapolation, at 0.0050 T it might be possible to reduce the backstreaming limit by 37%. If the field could be increased even further to 0.0100 T, then based on the extrapolation, the reduction might be over 70%.

The reported reductions in the electron backstreaming limit with magnetic field strength can be used to add engineering margin. One question concerning the data, however, is how do the reductions scale with the beam voltage? In order to access this question a plot of the fractional change of the backstreaming limit at different beam voltages was generated. In general, the backstreaming limit increases with increasing beam voltage. A plot of the fractional change in the backstreaming limit as a function of beam voltage is shown in Figure 7. As can be seen in the figure, the percentage at which the backstreaming voltage limit is reduced is independent of the beam voltage. This data suggests that the magnetic field reduces the electron backstreaming voltage limit by a fixed percentage rather than a fixed increment in voltage. This percentage apparently depends on the magnitude of the magnetic field. If this scaling holds for full-scale optics then, over the field range investigated in this work (0-0.0030 T), the backstreaming limit reduction fraction should also approach values of order 20%. In this regard, for example, a 154 V backstreaming limit (NSTAR, 2.3 kW) might be reduced by over 31 V at 0.003 T G.[3] At higher field strengths, this reduction can be even higher. The magnetic grid approach could extend the ion engine lifetime by allowing operation at lower accelerator grid voltages to prevent electron backstreaming. An investigation of the implementation of this approach to a full scale set of optics over a larger magnetic field and current density range to further validate these findings is left to a future investigation.

Use of a permanent magnet array to impose the B Field

As mentioned earlier, another possible means of imposing a transverse magnetic field across the downstream face of a multi-aperture accelerator grid is to use permanent magnets. The most straightforward way to implement this approach is to use thin bar magnets of alternating polarity between aperture rows.

These magnets generate the appropriate magnetic field required to reduce the backstreaming limit. Because magnets tend to weaken at elevated temperatures, this approach is viable for engines operating under conditions where the accelerator grid temperature is well below the magnet Curie limit. An alternative to implementing the permanent magnet approach is to use a magnetic circuit. In this scheme, magnetic flux is transported to the required areas via magnetically conducting metals. Figure 8 illustrates a possible magnetic circuit to generate the appropriate transverse magnetic field. This scheme was implemented on a 45 aperture molybdenum accelerator gridlet using samarium cobalt magnets and a mild steel magnetic circuit. The strips were approximately 1.5 mm thick. This scheme generated a symmetrical field profile across the optics with the peak field occurring at the center. The field was weakest (~0.0025 T) slightly off centerline. It is assumed that the backstreaming limit shift is a function of the magnetic field strength. As the accelerator grid voltage is reduced, electron backstreaming is expected to occur first at those regions where the magnetic field is weakest due to the larger transverse diffusion coefficient there. Figure 9 illustrates the reduction fraction of the backstreaming limit versus beam voltage for the geometry depicted in Figure 8. As can be seen in this case, the reduction fraction is approximately 16% and is constant as similarly observed in the electromagnet study over the entire beam voltage range investigated. This data also suggests that the magnetic field reduces the B=0 T backstreaming limit by a fixed fraction and not a simple voltage decrement.

Conclusions

The effect of a transverse magnetic field, imposed on the downstream side of the ion engine accelerator grid on electron backstreaming was studied. Data suggest that the imposed magnetic field reduces the magnitude of the backflowing electron current at the electron backstreaming voltage limit. Additionally, the absolute value of the electron backstreaming voltage limit was found to decrease linearly with increasing magnetic field strength. The percent reduction in the backstreaming voltage limit was independent of beam voltage. This percent reduction increased with increasing magnetic field strength. The data suggest that the transverse magnetic field approach could be used to add engineering margin, allowing the thruster to operate at reduced accelerator grid potentials thereby enhancing grid lifetime.

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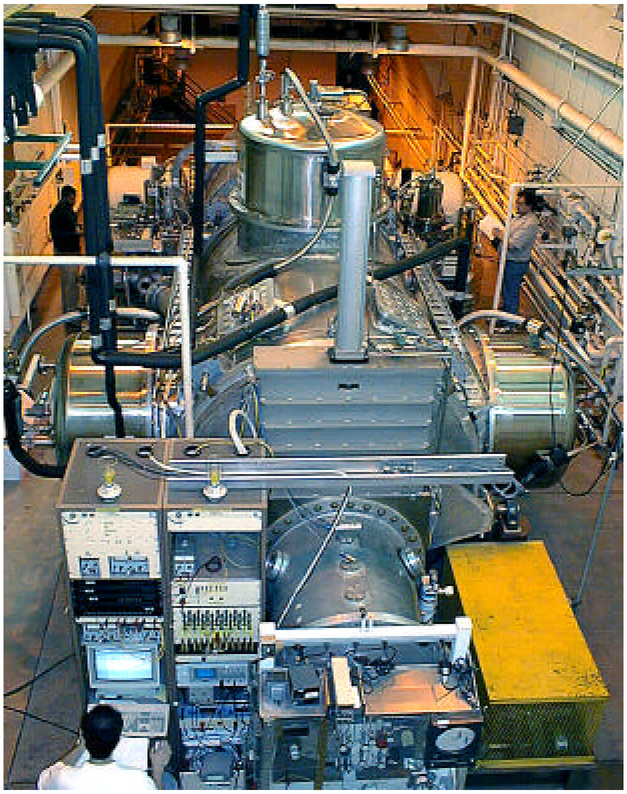

Figure 1. Photograph of Vacuum Facility 11.

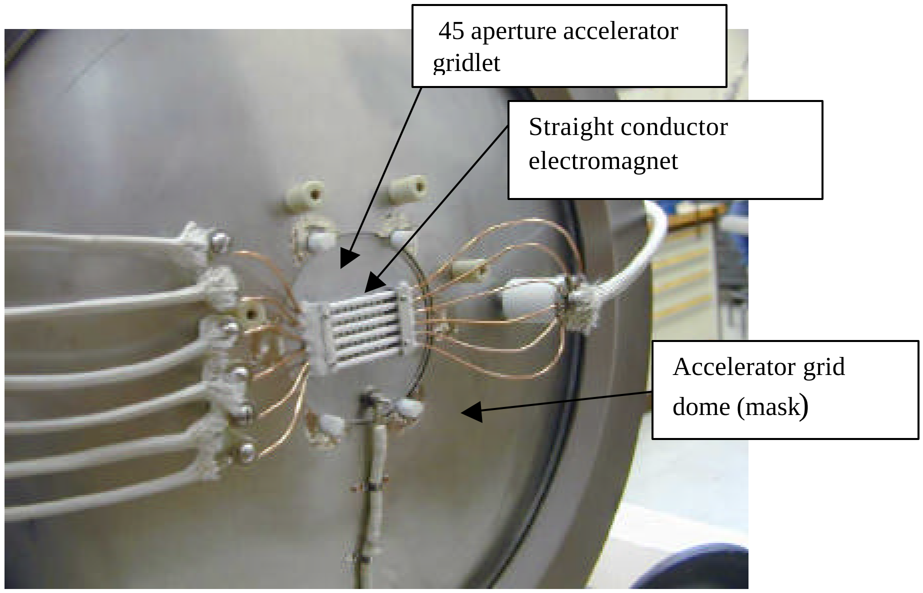

Figure 2. Ion optics hardware used in the investigation. Note the masked down optics and the active gridlet. Magnetic field is generated by currents that run though tubing (white).

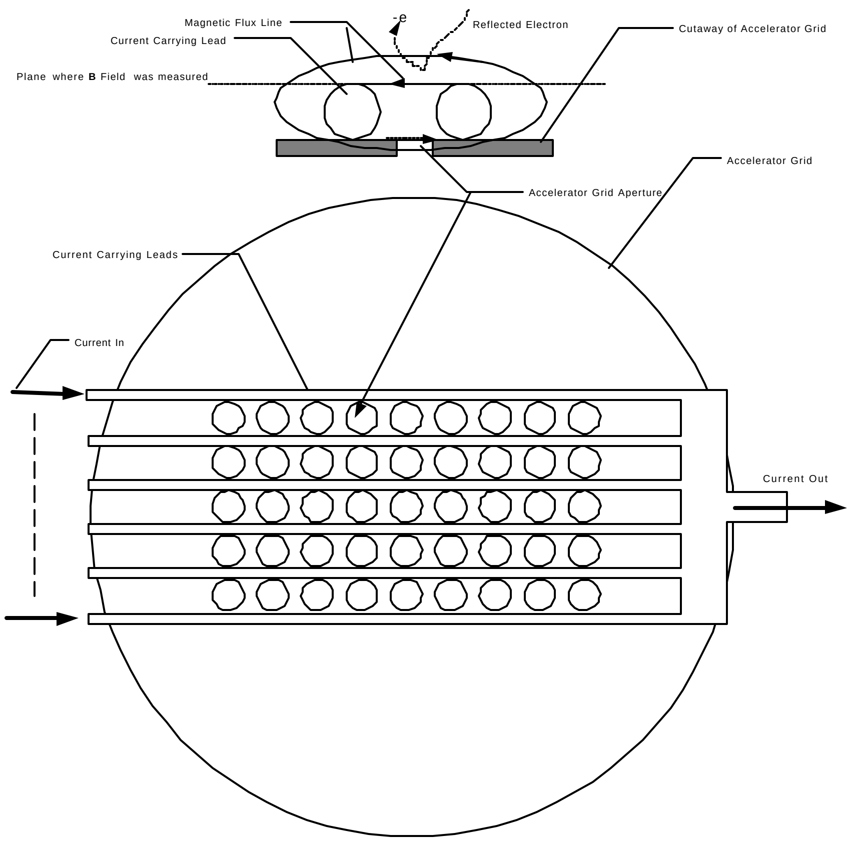

Figure 3a. Schematic depicition of magnetic grid concept utilizing straight conductors to generate magnetic field across apertures.

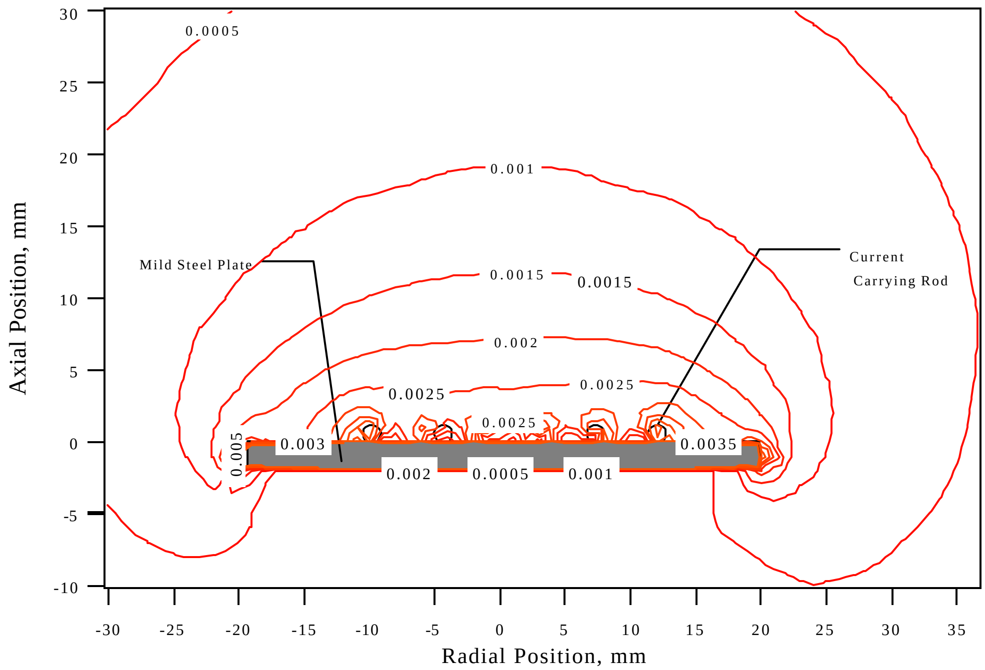

Figure 3b. Magnetic field contour plot generated by straight conductor configuration used in this investigation. Notice the magnetic field contours that form downstream of the gridlet. The magnetic field acts to prevent the back-diffusion of electrons into the engine. Magnetic field units: T.

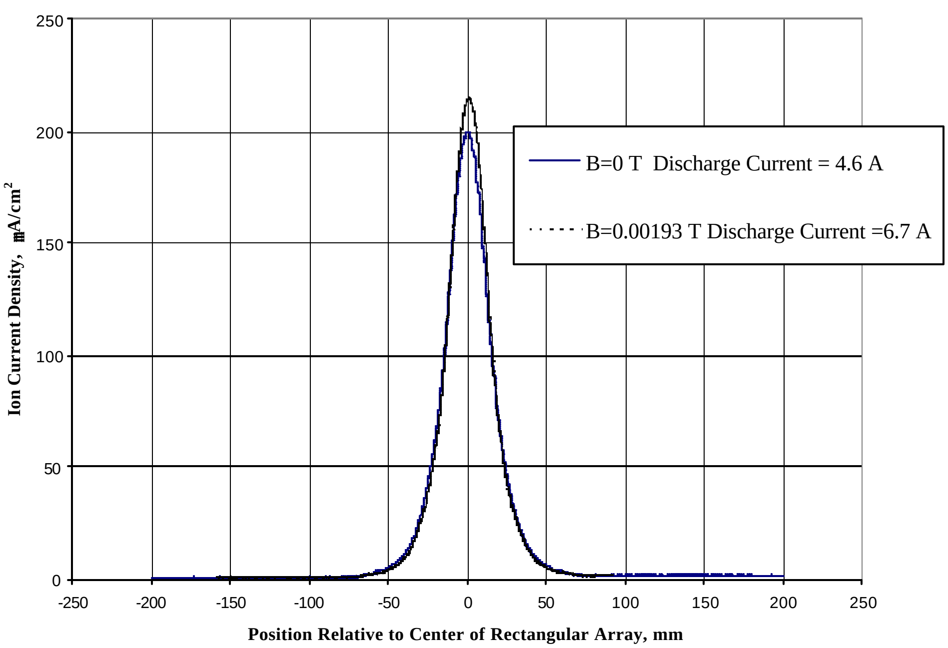

Figure 4. Comparison of ion beam profile with and without imposed magnetic field present.

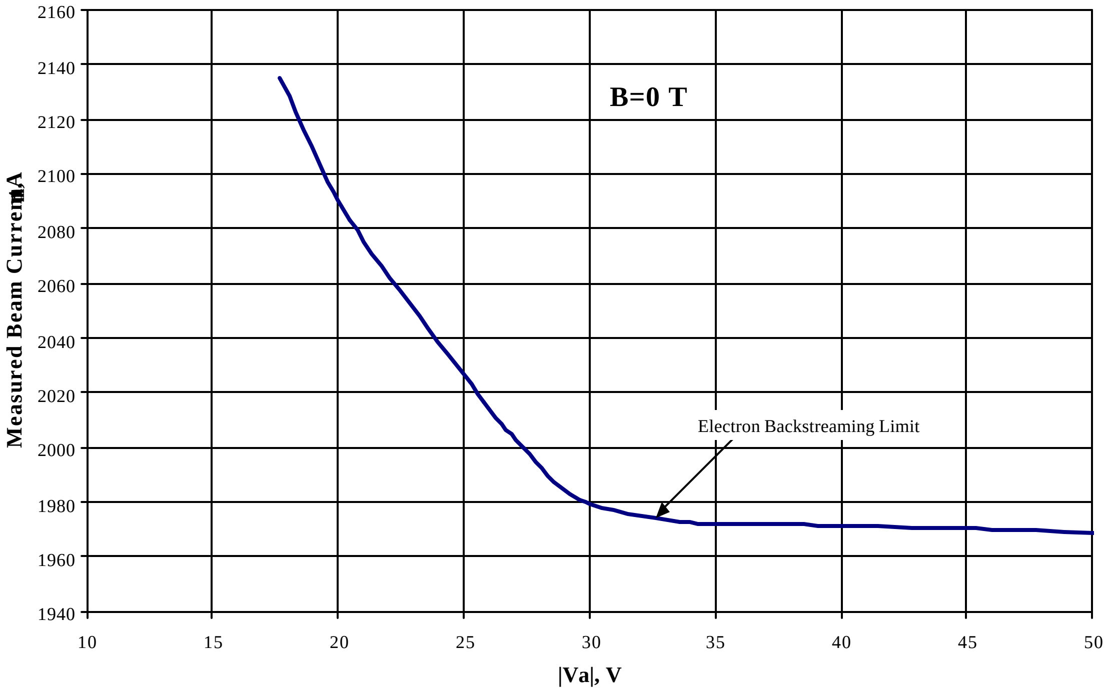

Figure 5a. Current-voltage characteristic used to determine the electron backstreaming limit. Beam voltage: 1050 V, Beam Current: 1.95 mA.

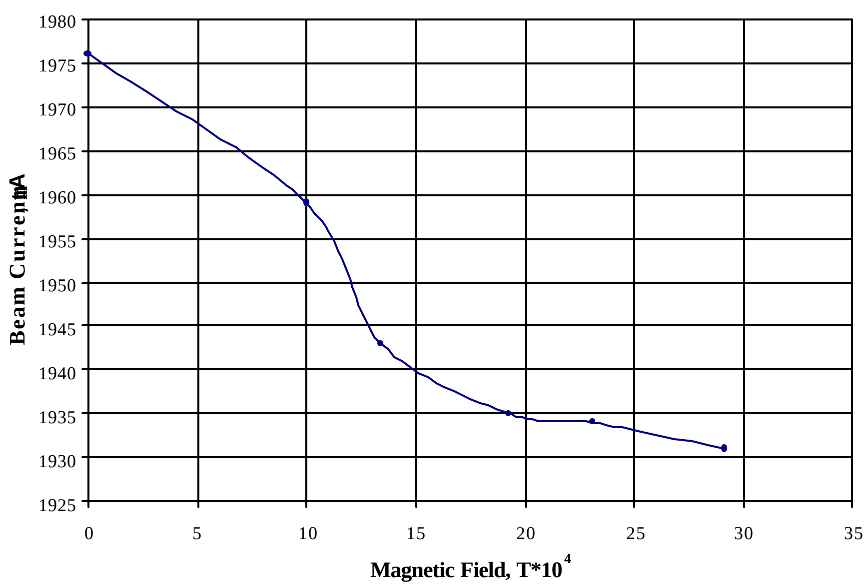

Figure 5b. Variation in the measured ion current at the backstreaming voltage limit as a function of magnetic field strength. Beam voltage: 1050 V

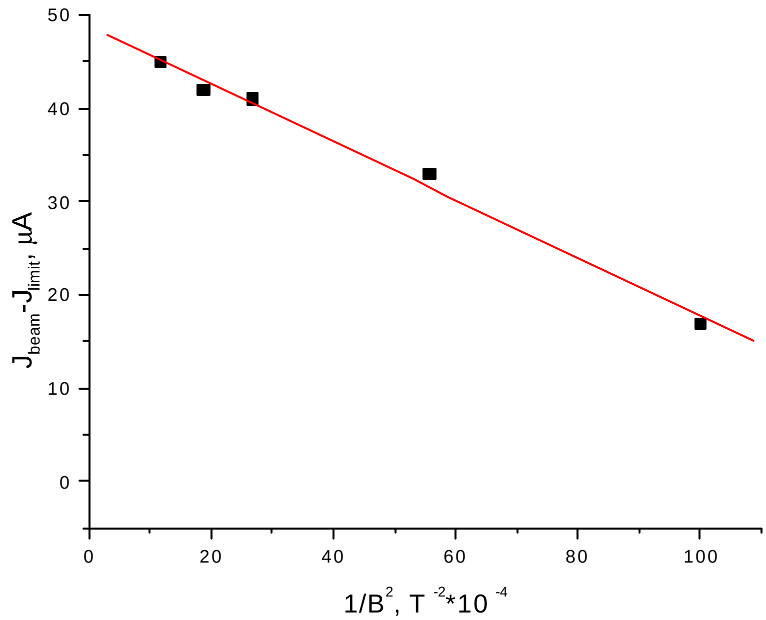

Figure 5c. Reductions in the measured "apparent" ion current at the backstreaming limit as a function of $1/B^2$. Note the variations are linear suggesting attenuation is due classical transverse diffusion.

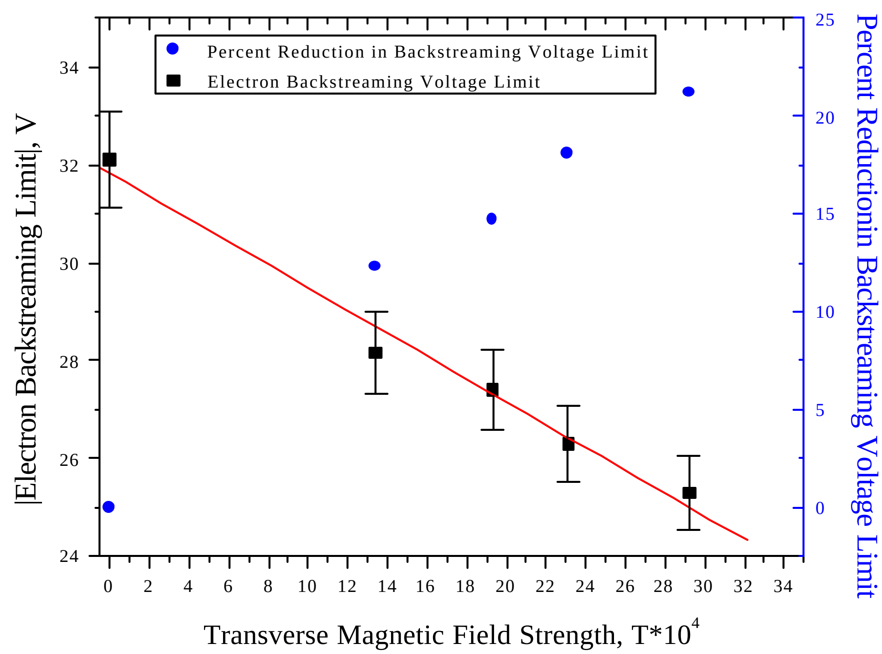

Figure 6. Reduction in the electron backstreaming limit with increasing magnetic field strength. Beam voltage=1050 V, beam current =1.95 mA.

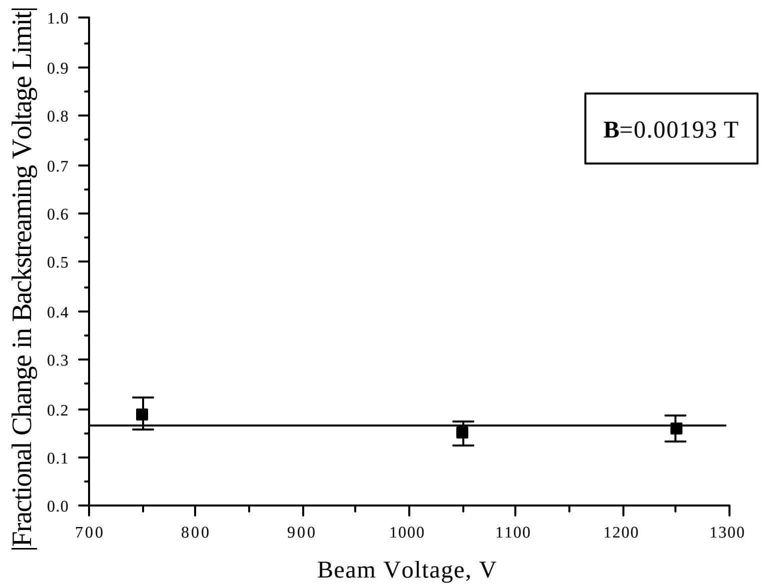

Figure 7. Fractional change in the backstreaming limit as a function of beam voltage. Beam voltage=1050 V, beam current =1.95 mA.

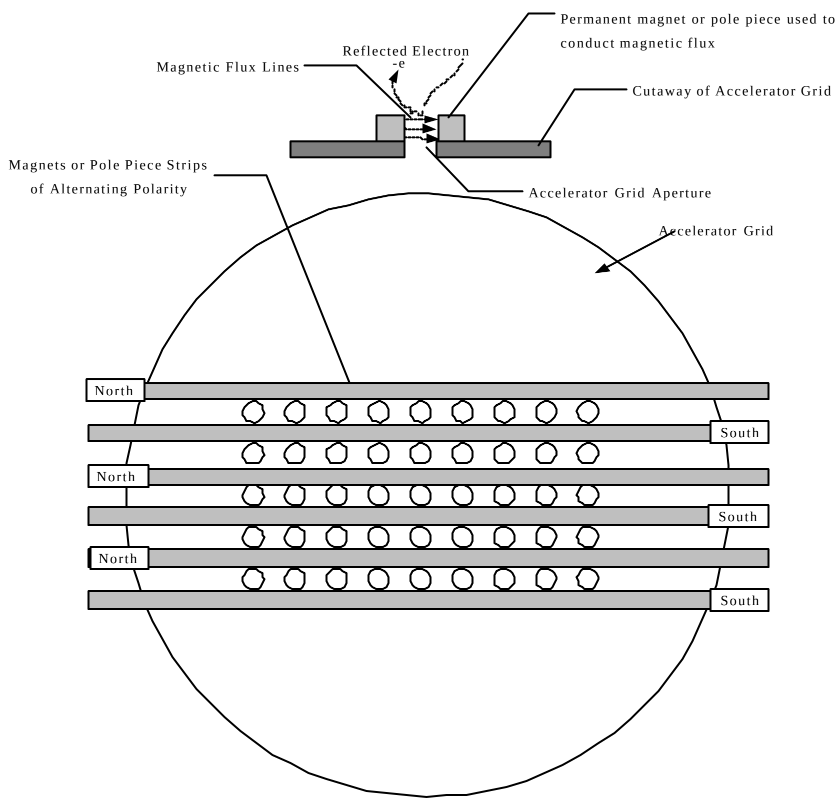

Figure 8. Schematic of magnetic grid approach utilizing permanent magnets in a magnetic circuit. Magnetic flux follows bars between apertures. Each bar has alternating polarity. Some external magnetic circuit components such as yokes and pole pieces are omitted for simplicity and clarity.

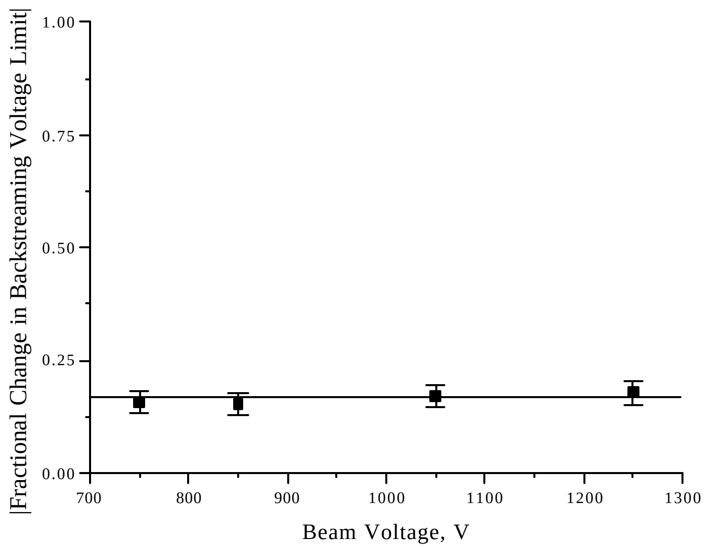

Figure 9. Fractional change in the backstreaming limit as a function of beam voltage. Data in this figure were taken with permanent magnet circuit similar in configuration to Figure 8.