Plasma Lens Focusing of the Hall Thruster Plume

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Abstract: The plasma lens is known to focus neutralized ion beams from gridded ion sources to high intensities at a focal point. The Hall thruster produces a beam that is more difficult to focus because of its large divergence and ion energy spread, but a relatively small reduction in the plume divergence could be technologically beneficial. We have demonstrated that the plasma lens can operate in the plume of a Hall thruster without strongly affecting the thruster discharge. Experiments were conducted using an electrostatic plasma lens placed in the thruster plume at different distances from the low power cylindrical Hall thruster. It is shown that large power consumption by the plasma lens electrode may limit practical applications of the plasma lens for space propulsion.

Nomenclature

L = Distance from thruster to Plasma Lens
V_L = Voltage on the Plasma Lens Electrode

I. Introduction

The electrostatic plasma lens[1,2] (PL) has been experimentally demonstrated[3,4] as a means to focus neutralized ion beams. It works by creating a region of crossed electric and magnetic fields using a set of magnetic coils and electrodes on the periphery of the beam. As the beam passes through this region, the ions are accelerated by the electric field so that their trajectories come to a focus downstream of the PL. In previous experiments, a gridded ion source was used to create a low-divergence, mono-energetic ion beam that was passed through the PL and brought to a high intensity at the focal point.

Hall thrusters produce neutralized ion beams with larger current density than is achievable with gridded ion sources because the acceleration takes place in quasi-neutral plasma and is not subject to space charge limitation. However, because the accelerating electric field is self-determined by the plasma in crossed electric and magnetic fields and not imposed by a metal grid, the Hall thruster plume suffers from a large divergence with plume half-angles of about 45 degrees for common thrusters[5] (the plume angle is taken to enclose 90% of the total current). The large divergence can cause problems because high-energy ions at large angles

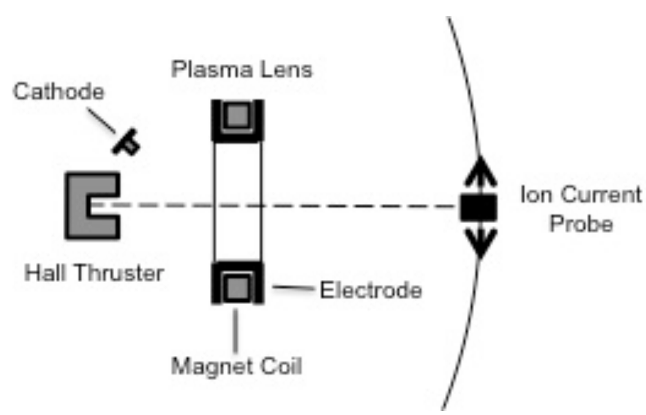

Figure 1. Experiment Schematic. *We placed the plasma lens in the plume of the Hall Thruster. An ion current probe on a rotating arm measured the current density downstream from the PL.*

can damage spacecraft components in their path.

Previous efforts to reduce plume divergence in Hall Thrusters have focused on optimizing the shape of the magnetic field in the Hall thruster channel[6,7,8] or adding ring-shaped electrodes to the channel walls in order to control the electric field that accelerates the ions[5,8]. However, the acceleration process in the thruster channel is strongly coupled to ionization of the gas flow and electron transport to the anode. If a PL outside a Hall thruster can be used to decrease the plume divergence it may de-couple the focusing of the ion beam from the ionization and acceleration of the beam. It is possible that this increased flexibility can improve thruster performance if the thrust gains from plume focusing can compensate for the additional power losses that are introduced.

In the course of developing a separate experiment that uses a Hall thruster as a source of highly ionized plasma for an experiment in the plume, we had the opportunity to test the basic principle of using a PL to focus the plume of a Hall thruster. The experiments were performed using a configuration that is not optimal for actual thruster performance improvement and the intent was merely to test the principle and identify any major problems with the device.

II. Setup

A schematic of our setup is shown in Fig. 1. We used a cylindrical Hall thruster[9] operating with a 250 V acceleration voltage and about 0.8 A discharge current. The PL consisted of a single magnet coil surrounded by an electrode. The PL was placed a distance L in front of the thruster and a guarding ring “plume probe” mounted on a rotating arm measured ion current for in a 180° arc at a radius of 73.2 cm from the thruster. We tested the PL at three different positions, L = 10.5, 15.5, and 37cm. The PL did not enclose the entirety of the plume current in any of these positions, and in the furthest position only 10% of the total current passed through the center of the PL. This is obviously not optimal for focusing performance, but it is sufficient to test the basic principle. The magnet coil in the PL had 223 windings and was powered with currents ranging from 1-3A. The combined magnetic field produced by the thruster magnets and the PL with 2.5 A in the magnet coil is shown in Fig. 2. The field strength at the center of the PL is approximately 40 Gauss. The electrode was biased to a positive voltage in the range of 0-125V with respect to the thruster cathode, which was grounded. Larger voltages on the PL were not tested because of the large electron current drawn by the electrode at these voltages. The current drawn by the PL electrode is discussed in section III. We measured the plasma potential near the PL using a floating emissive probe on a moveable positioner and we measured ion energy with a Retarding Potential Analyzer (RPA) that was located downstream of the thruster.

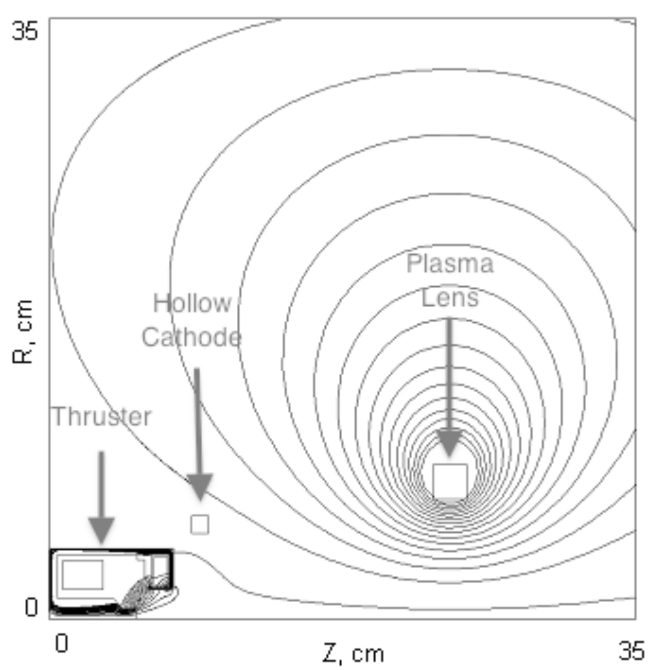

Figure 2. Magnetic Field Line Plot. *The magnetic field line plot for the combined field of the thruster and the PL is shown for the case where the PL is 15.5cm in front of the thruster channel exit and the current in the coil is 2.5 A. The field strength at the center of the PL is approximately 40 Gauss.*

III. Effect of the Plasma Lens on Thruster Operation

An important question is whether introducing the PL into the plume alters thruster operation or merely acts on the plume, leaving the processes in the thruster channel unchanged. The PL could interfere with thruster operation either by modifying the magnetic field inside the thruster or possibly by drawing large electron currents. For two of the PL positions we tested, L= 15.5 and 37cm, the PL magnetic field did not greatly alter thruster operation. When the PL magnetic field was turned on but the electrode was left floating, measurements of the discharge current and the angular ion current in the plume were unchanged. However, when the PL magnetic field was turned on with the PL in its closest position, L=10.5cm, thruster operation was strongly affected. The peak ion current density measured by the plume probe dropped by 40% and the discharge current decreased by 12%. This is probably because the magnetic field from the PL affects the field inside the thruster channel and degrades the magnetic configuration.

When the electrode was biased positively with respect to the grounded thruster cathode, it drew large electron currents, up to 2.5A. For the largest currents, the thruster discharge current decreased by up to 5%, but for current below 1A, the discharge current was unchanged, suggesting that the thruster operated normally.

The current drawn by the PL had a strong dependence on the location of the PL as well as the strength of the PL magnetic field. Fig. 3 shows the current to the PL vs. electrode voltage for the three positions that were tested. The current to the PL decreased as the distance between the thruster and the PL was increased. One possible explanation for this is that the electrode draws less current because the plasma density is lower further out in the plume. If this were true it would suggest that the current to the electrode at any given axial position could be decreased by increasing the radius of the PL because the plasma density decreases for larger radius. The current to the PL also had a strong dependence on the magnetic field, decreasing roughly as the inverse of the field strength.

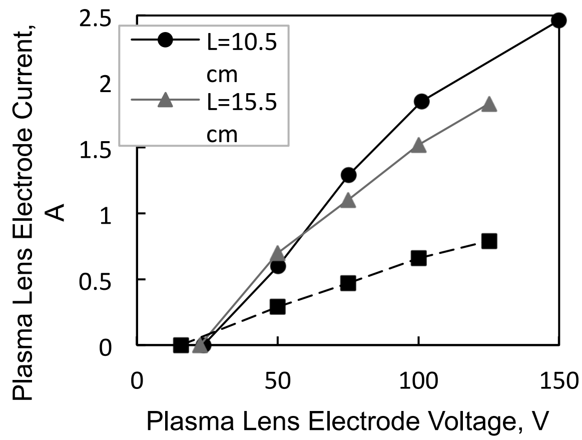

Figure 3. Current to the PL Electrode. *The PL electrode drew large current, up to 2.5 A. These currents were reduced for lower electrode voltages and when the PL was placed further from the thruster.*

IV. Effect of the Plasma Lens on the Thruster Plume

Figure 4 shows measurements of the plume ion current vs. angle for the case where the PL magnet coil has zero current and the PL electrode is floating at +6.4 V compared to the case where the magnet coil is powered with 2.5 A (producing a field shown in Fig. 2) and the electrode is biased at +100V with respect to the thruster cathode. These measurements were taken with the PL in the position L=15.5cm. It is clear that the PL has a large effect on the ion current profile in the plume. It is possible to determine which portion of the ion current passed through the center of the PL and which portion passed outside because they are separated by the "shadow" in the ion current that appears at +/-28 degrees. This shadow is produced because the PL physically obstructs the path of some ions. When the PL is activated it focuses the current that passes through it and it defocuses the current that passes outside, pushing it to higher angles. The fraction of the total current that passes through the PL is 0.48, and this remains constant whether the PL is on or off. With the PL off, the 90% half plume angle is 53.5° and the 90% half plume angle for the "inside current" that passes through the PL (current at less than

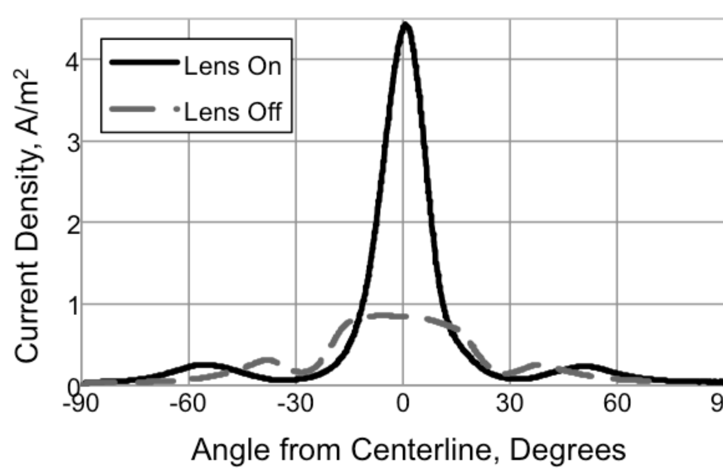

Figure 4. Ion Current Density vs. Angle in the Plume. *The curve labeled 'lens off' was measured with zero current in the PL magnet and the PL electrode at its floating voltage of +6.4V above the grounded thruster cathode. The curve labeled 'lens on' was taken with 2.5A in the PL magnet (field lines shown in Fig. 2) and +100 V on the PL electrode.*

+/-28°) is 23.8 degrees. When the PL is turned on, the half plume angle for the total current increases to 64.2° while the inside current half plume angle decreases to 19.4°. This decrease in the half plume angle for the inside current is not very large. One reason may be that the PL electrode depletes electrons form the plume causing the plume to diverge after the PL due to space charge repulsion. Adding a second cathode after the PL could eliminate this effect.

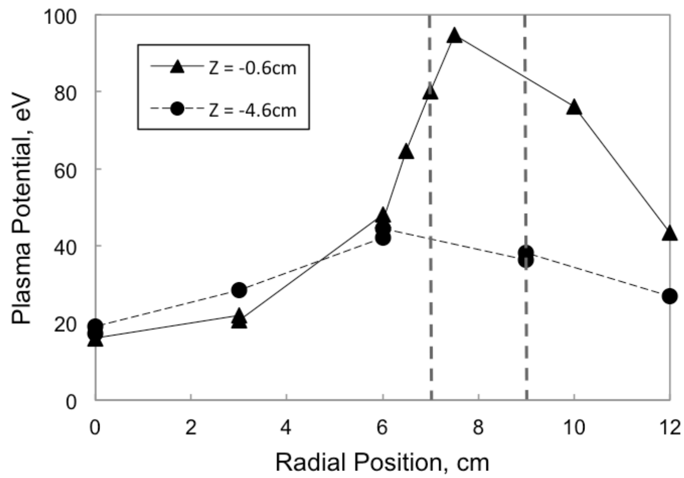

Figure 5. Plasma Potential Measurements. *Plasma potential measured with the PL located at L=10.5cm and the electrode biased to +100V. Radial measurements of the plasma potential were performed using a floating emissive probe at Z=-0.6 cm and Z=-4.6cm upstream of the PL. The vertical dashed lines show the radial location of the PL electrode.*

V. Plasma Potential Measurements

We used a floating emissive probe on a moveable positioner to measure the plasma potential near the PL. Measurements were only performed when the PL was positioned at L=10.5cm because of the limited reach of the probe positioner. Figure 5 shows these measurements vs. radial position taken at two axial distances from the PL with the electrode biased to +100V. The measurements show that the PL electrode successfully introduces an electric field into the plasma with a radial voltage drop of about 80 V just in front of the PL.

VI. Ion Energy Measurements

The ion energy distribution, plotted in Fig. 6, is normalized to the peak value of each curve in order to demonstrate a shift in the average energy. When the voltage on the PL is increased, the average ion energy measured on the centerline decreases by 15 V. This decrease is probably due to a combination of two effects. First, the RPA only measures energy associated with the ion velocity component that is perpendicular to the face of the RPA. Ions that come in at an angle θ will register as lower energy ions by a factor of $\cos^2(\theta)$. Therefore, ions that are focused toward the center will come in at an angle and reduce the average energy that is measured. The second effect that may play a role has to do with the energy spread of the ions in the thruster plume. Figure 6 shows that the Hall thruster produces a spread in the ion energy of about 50 V. The ions in the lower range of that energy spread will be more strongly influenced by the focusing electric field and will be focused to the center at lower PL electrode voltages than the higher energy ions. Therefore, if the PL electrode voltage is not high enough to bring the higher energy ions to a focus, then more of low energy ions will be measured at the center.

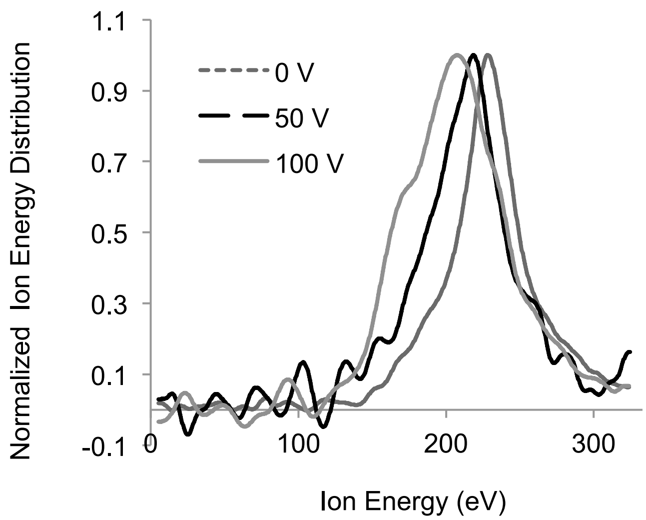

Figure 6. Ion Energy Measurements. *Measurements of the ion energy distribution with a retarding potential analyzer downstream of the thruster and PL. Measurements were taken with and with 2.5 A in the PL magnet and 50 V and 100 V on the electrode.*

VII. Conclusion

We have demonstrated that the electrostatic plasma lens can operate in the plume of a Hall thruster without greatly affecting the thruster operation and can modify the divergence of the ions in the plume. We have also identified significant obstacles to a practical implementation of this device. In our configuration the PL electrode drew about 1.5 A of current at 100V, consuming 150 W of power. This is far too large compared to the 200 W consumed by the thruster discharge. It is possible that this could be reduced by increasing the radius of the PL so that it sits in an area of the plume where the plasma is less dense, or by adjusting the location of the cathode so to a location that has more magnetic insulation from the PL electrode. It might also be possible to reduce the power consumption by decreasing the size of the PL electrode so that less current is collected or by increasing the magnetic field of the PL and adjusting the thruster configuration so that the field in the channel is not disturbed. The setup could also be improved by using permanent magnets for the PL to decrease power consumption, and possibly by adding a second cathode after the PL to ensure that the plume is neutralized.

In our current configuration we approximate that adding the PL to the thruster increases the thrust by up to 12%. This approximation was done by assuming all ions are mono-energetic and singly ionized and calculating the thrust from the plume ion current measurements. This is far too small to compensate for the power losses that are increased by 75% (not including losses in the magnetic circuit). There is room for improvement in this figure because, due to limitations in our setup, 52% of the plume current does not pass through the PL and is in fact de-focused.

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