Technical Notes

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Reduction of Plasma Loss to Discharge Chamber Walls in a Ring-Cusp Ion Thruster

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Introduction

IN a magnetic cusp ion thruster, the plasma ion loss to the discharge chamber wall has a significant influence on the discharge performance expressed in terms of ion production cost and propellant utilization efficiency.[1] Recent experimental results[2,3] indicate that the plasma ions not only leak at the cusps, but also escape to the areas between the cusps traveling across the magnetic field lines of the cusps. This ion loss between the cusps would be substantial if the thruster was operated with a massive propellant such as xenon. For xenon plasmas, the ion Larmor radius at the intercusp regions becomes comparable to or larger than the characteristic length of the cusp, i.e., the pole width of magnet, predicting that such a cusp ion thruster provides a weak confinement of the plasma ions. To reduce the ion loss rate to the chamber walls, it is necessary to confine the ions electrostatically rather than electromagnetically in the discharge chamber.

This Note presents a method for improving the discharge performance by confining the ions electrostatically in the discharge chamber. A set of ring-shaped electrodes biased positively with respect to the chamber walls (anode) were installed in the regions enclosed by the cusp fields.

Experimental Apparatus

A ring-cusp discharge chamber, as shown in Fig. 1, consists of a stainless steel bucket with a diameter of 20 cm and a length of 20 cm, and is externally surrounded by six rows of permanent magnets. The spacing between the magnetic rows is 33 mm. Each magnet, made of samarium/cobalt, produces a field strength of about 4 kG at its pole surface. The chamber walls including the rear plate act as an anode; the arc discharge is struck between this anode and the cathode composed of six pieces of 0.35-mm-diam tungsten filaments. The screen grid is directly connected to the cathode in order to repel even the high-energetic primary electrons emitted from the cathode surface.

One feature of this ion chamber is that it installs a set of ring-shaped electrodes that are electrostatically isolated from the anode and can be biased at any potential. Each electrode (which we call interelectrode) is located at the middle of each pair of magnets. The role of these interelectrodes is to reduce the ion loss to the chamber walls by making positive potential hills in the intercusp regions (the regions between the cusps that are enclosed by the magnetic field lines).

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A cylindrical Langmuir probe (0.35 mm in diameter by 1.2 mm long) is inserted into the discharge chamber to measure the ion density and electron temperature of the discharge plasma. As for the measurement of the space potential, we use an emissive probe[4] with a 50-μm-diam tungsten wire that is heated by the passage of external current. The space potential is derived from the knee in the semi-log plot of the probe characteristic, which appeared sharply at any probe position when the heating current was increased to 0.8 A. Both probes were movable in the axial and radial directions by the traverse unit with two stepping motors.

In the present experiment, the discharge current (I_d) was 3–15 A, the discharge voltage V_d was adjusted to 30 or 40 V by varying the filament heating current, and the propellant flow rate $\dot{m}$ was 0.5–2 A equivalent.

Results and Discussion

Figure 2 shows the density distributions of the ion saturation currents for the argon and xenon propellants. For the measurements, a Langmuir probe was scanned parallel to the chamber axis, while its radial position is maintained to be a constant distance from the wall surface (2 mm). Both the density distributions have large peaks that appear at positions corresponding to the location of the permanent magnets. This indicates that, at the center of the cusp, plasma ions produced in the field-free region can easily leak at the wall traveling along the field lines. According to the measurement by Leung et al.,[5] the leak width at the cusp scales as a hybrid Larmor radius r_h, where $r_h = (r_e r_i)^{1/2}$, r_e and r_i being the Larmor radii of electrons and ions, respectively, which can be approximated by $4r_h$. The half-widths of the peaks shown in Fig. 2 are of the same order, but decrease by approximately one-half with interelectrodes. Furthermore, installing the interelectrodes brings about a considerable decrease of the ion saturation current in the regions close to the center of cusps and results in the reduction of the ion loss rate to the chamber walls by approximately 43 and 54% for argon and xenon, respectively.

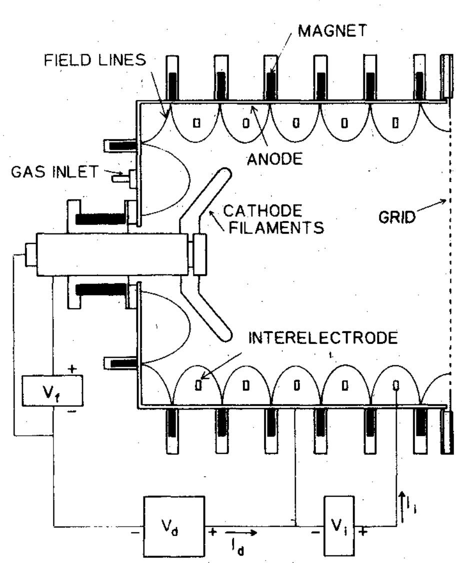

Fig. 1 Ring-cusp discharge chamber.

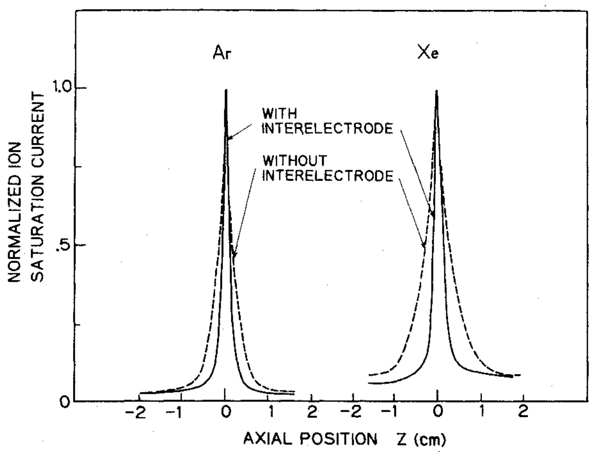

Fig. 2 Density distributions of ion saturation currents for argon and xenon plasmas at $\dot{m}=1$ A, $V_d=40$ V, $I_d=5$ A.

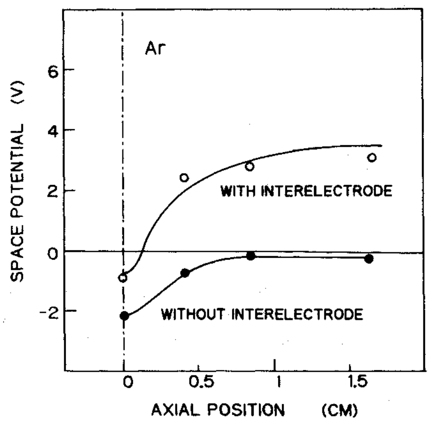

Fig. 3 Spatial potential distributions at the wall surface with and without interelectrodes.

Figure 3 shows the axial distribution of the space potential at the wall surface (expressed in values relative to the space potential at the chamber axis) operated with and without interelectrodes for the same operating condition as seen in Fig. 2 ($\dot{m}=1$ A, $V_d=40$ V, $I_d=5$ A). This result was obtained from the emitting probe that was scanned on the same trace as the previous density measurement. The potential valley is seen at the center of the cusp for operations both with and without interelectrode. This fact may be explained as follows. The electron generated in the field-free region hardly penetrates into the intercusp region traveling across the magnetic field lines because of its extremely small Larmor radius (0.1 mm), while the ion can easily penetrate the region. This situation produces a strong space charge electric field that ensures charge neutrality.[6] Although the space potential is negative at any axial position without an interelectrode, it turns out to be positive except at the region around the center of the cusp with an interelectrode. At present, we do not have information to explain the mechanism of this potential rise, but it may be considered that electrons, magnetically trapped in the intercusp region, are collected and absorbed into the positively biased interelectrodes, thus raising the space potential in the intercusp region. In this situation, the plasma ions escaping from the field-free region will experience a repulsive electrostatic force and be reflected back before reaching the wall surface, resulting in the reduction of the ions lost at the walls after passing through the intercusp region.

Figure 4 is a plot of the rate of increase of the ion density averaged over the screen grid surface ($\Delta N_i/N_i$) as a function of the fraction of the additional power supplied to the interelectrodes to the discharge power ($\Delta P/P$). The ion density

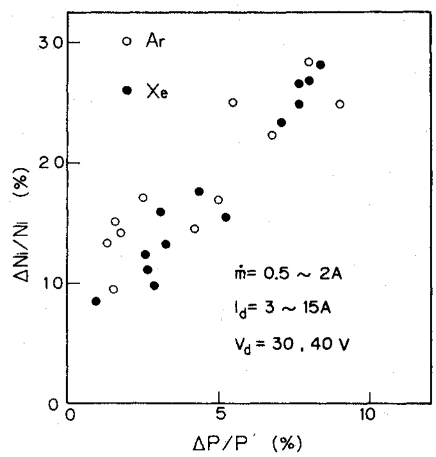

Fig. 4 The rate of the increase in ion density as a function of the fraction of the additional power to the discharge power.

increases almost linearly with the additional power and its rate is independent of discharge parameters such as the discharge current, propellant type, and propellant flow rate. About a 30% increase of the ion density can be attained when only 8% of the electric power is added to the discharge chamber. This result indicates that the installation of the interelectrodes is an effective method for reducing the ion loss to the chamber walls and improving the discharge performance.

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Off-Design Analysis of Counter-Rotating Propeller Configurations

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Introduction

In a recent investigation, Playle et al.[1] and Korkan and Playle[2] conducted studies to develop a theoretical method by which counter-rotating propellers could be designed and

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