Thrust Characteristics of High-Density Helicon Plasma Using Argon and Xenon Gases

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A helicon plasma thruster has been studied to develop a completely electrodeless electric thruster using high-density helicon plasmas. The proposed helicon plasma thruster involves two processes: the generation of source dense plasma by using a helicon wave, and the additional acceleration of the generated plasma by using the Lorentz force generated by the product of the induced azimuthal current and external radial magnetic field. This additional acceleration method requires additional electrodes or coils, leading to a longer discharge tube. Therefore, it is necessary to find a good configuration that minimizes wall losses within the discharge tube. Here, thrust characteristics such as thrust, thrust-to-power ratio, specific impulse, and thrust efficiencies of argon and xenon gases were studied, using a radio frequency of 7 MHz and an input power less than 3 kW, to optimize the target plasma without employing an additional acceleration method. A helicon plasma source, with electromagnets and permanent magnets, was used to generate a flexible divergent magnetic field, and a target-type cylindrical thrust stand was installed in a large buffer chamber (volume: ≈0.26 m³, pumping speeds: 1000 and 2400 l/s). In the case of argon gas, the maximum thrust and the thrust-to-power ratio were 21 mN and 8.3 mN/kW, respectively, whereas in the case of xenon gas, these values were 40 mN and 16 mN/kW, respectively.

I. Introduction

HELICON plasma is known to have a high production efficiency and uses an external magnetic field and RF power [1]. Because helicon plasma can be generated under a wide range of operating parameter (e.g., strength of the magnetic field, filling pressure, and excitation frequency of RF power [2,3]), it is actively used in various fields such as plasma processing and electric propulsion. High-density helicon plasma has promising applications in the field of thrusters because electric thrusters have a greater specific impulse in comparison to chemical thrusters. However, conventional electric thrusters, such as the ion engine, Hall thruster, and Magnetoplasmadyne (MPD) thruster, suffer from the common problem of erosion of the electrodes that are in direct contact with the plasma, leading to reduction in their life span [4]. However, the helicon plasma thrusters can be built using an antenna that is wound around the outer surface of a discharge tube, thereby avoiding contact with the plasma. Hence, helicon plasma thrusters are being developed intensively by numerous research groups as a solution to the problem of electrode erosion.

Here, two different types of helicon plasma thrusters are proposed. The first one uses an active acceleration method. An example of the this type is the variable specific impulse magnetoplasmadynamic rocket (VASIMR) [5,6] that uses superconducting magnets in addition to a high-power ion cyclotron heating system, which enables additional acceleration. The second one is a passive acceleration thruster that uses a magnetic nozzle to generate plasma acceleration (e.g., [7,8]). Both types of thruster have their own advantages. The first type allows for the thrust and specific impulse to be easily controlled independently, whereas the second one has a simple system.

Several experiments have been conducted on the active-acceleration-type helicon plasma thruster. The helicon electrodeless advanced thruster (HEAT) project [9] was proposed by one of the authors. Initially, a dense plasma was generated using the helicon wave with an RF source at a frequency ranging between the ion and electron cyclotron frequencies. Finally, the dense target plasma was accelerated using the Lorentz force \( f_r \), which is a product of the induced azimuthal current \( j_\phi \) and external radial magnetic field \( B_r \), to obtain a higher thrust. Several methods (e.g., rotating magnetic field acceleration and \( m = 0 \) coil acceleration) have been proposed to induce \( j_\phi \) by using active power sources in plasma in the HEAT project, and these have been studied extensively through both experimental and numerical analyses to prove the acceleration principle [9,10]. Here, it is essential to understand the characteristics of plasma as a target source that can be applied by the acceleration method, leading to its optimization. Because the additional acceleration methods require a longer discharge tube, when accepting the acceleration schemes, it is necessary to identify a configuration that prevents additional wall losses within the discharge tube. In this study, the performance of source dense helicon plasma was studied using argon and xenon gases, focusing on the generation scheme only, without any additional acceleration methods.

To improve the thrust characteristics of the helicon plasma, two factors must be considered. First, wall loss must be reduced using a large diameter [11] or high magnetic field intensity, to decrease the gyro radius. Second, the axial ion velocity (or the ratio of the axial

Nomenclature

- \( B_r \): radial magnetic field
- \( F_r \): thrust
- \( F_z \): axial Lorentz force
- \( F_{\text{th}} \): thrust-to-power ratio
- \( \text{FR} \): volumetric flow rate
- \( f_{\text{RF}} \): excitation frequency
- \( g \): gravitational acceleration
- \( I \): current of electromagnets
- \( I_p \): specific impulse
- \( j_\phi \): induced azimuthal current
- \( m \): particle mass
- \( \dot{m} \): mass flow rate
- \( P_{\text{RF}} \): input power of excitation frequency
- \( T \): discharge duration
- \( v \): axial particle velocity
- \( z \): axial position
- \( \eta \): thrust efficiency
velocity to the radial velocity) must be increased by strong axial and radial magnetic fields due to the acceleration of the magnetic field gradient (magnetic nozzle) \[11\]. Previously, plasma thrust has been found to increase with increasing tube diameter (25–100 mm) \[11,13–16\], under a magnetic field of a several hundred gauss. According to \[11\], thrust also increased with an increasing \(B\). The aforementioned factors must be considered during the application of additional acceleration methods to the target plasma \[9\]. Note that such a case requires an additional length of discharge tube that may further increase wall loss.

Here, we have tested excellent thrust characteristics of the helicon plasma alone, considering the factors listed previously, using a larger tapered discharge tube (inner diameter ranging between 100 and 170 mm) to prevent the lines of the magnetic field (\(r = 0\) mm and \(z = -385\) mm) from intersecting the inner wall (resulting in a reduction of wall loss). A target-type thrust stand was employed, which is a reliable means of taking indirect thrust measurement \[17\].

II. Experimental Setup

A large mirror device (LMD), as illustrated in Fig. 1a, was used as the source of helicon discharge \[18\] for this study. The LMD was composed of four parts; gas feeding and vacuum systems, magnetic field sources, an RF system, and electromagnetic acceleration systems, including a target-type thrust stand within the vacuum chamber.

The vacuum chamber of the LMD had two parts. The first part consisted of a tapered discharge tube, made of quartz, with an inside diameter (i.d.) ranging from 100 to 170 mm and an axial length of 1000 mm capable of housing, generation, and acceleration of antenna/coils, in addition to diagnostics parts. For example, an input power \(P_{RF} = m = 0\) coil and rotating magnetic field coils were installed in the tapered section. Note that acceleration coils were not used in this study. The second part consisted of a cylindrical vacuum chamber, made of SUS316, with an i.d. of 465 mm and an axial length of 1700 mm. The tapered discharge tube reduces wall losses in the magnetic nozzle region, considering the lines of the magnetic field. Two turbomolecular pumps (1000 and 2400 l/s) and two rotary pumps were connected at the end of the vacuum chamber, and the background pressure before feeding a propellant gas was less than \(3 \times 10^{-4}\) Pa. Argon and xenon gases were supplied continuously through the mass flow controller by using the head flange of the tube.

The external magnetic field was applied using 12 electromagnets and permanent magnets that surrounded the vacuum chamber \[7\]. The permanent magnets were placed at a straight section of the discharge tube to produce a radial magnetic field that facilitated acceleration of the plasma along the axial component. The magnetic field distribution generated by the electromagnets and the permanent magnets is illustrated in Fig. 1b. Three cases were tested with magnetic field coil current values of 200, 300, and 400 A, corresponding to magnetic fields on \(r = 0\) mm and \(z = -385\) mm of 1.1, 1.4, and 1.7 kG, respectively. The combined magnetic field of the two types of magnets controlled the magnetic field strength and field divergence to optimize plasma discharge and reduce wall loss in the magnetic nozzle region.

The RF system was composed of three parts, namely a half helical antenna, an impedance-matching circuit, and an RF power supply. The antenna was made of 0.5-mm-thick copper plate, which was wound around the outer surface of the discharge tube with an axial length of 185 mm to excite the azimuthal mode number \(n = \pm 1\). The typical RF power and its excitation frequency \(f_{RF}\) were \(\sim 3\) kW and \(7\) MHz, respectively. The pulsed discharge duration time \(T\) was taken as \(75\) ms, and the duty ratio was \(5\)%. An input RF power \(P_{RF}\) was derived by a subtraction of a backward RF power from a forward RF power by using a directional coupler.

A target-type thrust stand \[17\] using a cylindrical target was installed, as shown in Fig. 1a, in front of the open end of the discharge tube, \(z = 20\) mm. Plasma thrust \(F\), which is the sum of the plasma and the electromagnetic pressures, was measured from the displacement of the hanging target structure by using a laser displacement sensor (IL-S025, Keyence Co., reproducibility: \(1\) μm). The impulse was measured from the displacement of the target by using this sensor. The mean thrust was determined using the impulse and the discharge duration. The resolution of the thrust was calculated to be nearly \(0.2\) mN for a discharge of \(75\) ms. The cylindrical target comprised 14 disks made of polycarbonate and a cone-shaped end plate made of SUS316. Because the polycarbonate disks were located on the outer side of the plasma region and were not in direct contact with the plasma, they were not damaged by the helicon discharge. The ions and the neutral particles ejected from the quartz tube region entered the target and collided with the cone-shaped end plate. Injected particles transferred their momentum \(mv\) (\(m\): particle mass, \(v\): axial particle velocity) to the target (inelastic condition). If the cylindrical target was sputtered by the plasma, then thrust value was overestimated. However, there was no apparent damage visually observed after \(\sim 10,000\) instances of plasma discharge. The thrust was also confirmed through a comparative study by using the target-type thrust stand and a torsional-type thrust stand in the same thruster, respectively \[19\].

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**Table 1 Experimental parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input power (P_{RF})</td>
<td>~2.0 and ~3.0 kW</td>
</tr>
<tr>
<td>Discharge duration (T)</td>
<td>75 ms</td>
</tr>
<tr>
<td>Ar gas flow rate (FR)</td>
<td>30, 50 and 70 sccm</td>
</tr>
<tr>
<td>Pressure (discharge tube)</td>
<td>0.4, 0.6, and 0.75 Pa</td>
</tr>
<tr>
<td>Pressure (chamber)</td>
<td>0.06, 0.1, and 0.15 Pa</td>
</tr>
<tr>
<td>Xe gas flow rate (FR)</td>
<td>10, 50, and 90 sccm</td>
</tr>
<tr>
<td>Maximum magnetic field (B) ((r = 0) mm, (z = 385) mm)</td>
<td>1.1, 1.4, and 1.7 kG</td>
</tr>
</tbody>
</table>
III. Experimental Results

The measurements using argon and xenon gases were carried out using the parameters shown in Table 1.

Figures 2 and 3 show the experimental results of argon and xenon discharges, respectively. The mean thrust during discharge $F$ (newtons), thrust-to-power ratio $F/P_{\text{RF}}$ (newtons per watt), specific impulse $I_{\text{sp}} = FM/mg$ (seconds), and thrust efficiency $\eta = gI_{\text{sp}}F/2P_{\text{RF}}$ (percent) were derived as a function of $P_{\text{RF}}$. Here, $m$ and $g$ are mass flow rate (kilograms per second) and gravitational acceleration (meters per second squared), respectively. Note that a backflow effect may have been present, causing an overestimation of $I_{\text{sp}}$, because neutral pressures were high in the cases of high FR. The four parameters mentioned previously were measured under different $P_{\text{RF}}$, gas flow rate FR, and the magnetic field $B$ values. In the case of argon gas, the maximum values of $F$, $F/P_{\text{RF}}$, $I_{\text{sp}}$, and $\eta$ obtained independently were 21 mN ($B = 1.1$ kG, FR = 70 sccm, and $P_{\text{RF}} = 3$ kW), 8.3 mN/kW (1.4 kG, 70 sccm, and 2 kW), 2000 s (1.1 kG, 30 sccm, and 3 kW), and 6.3% (1.4 kG, 30 sccm, and 2 kW), respectively. In the case of xenon gas, these values obtained independently were 40 mN (1.4 kG, 90 sccm, and 3 kW), 16 mN/kW (1.4 kG, 90 sccm, and 2 kW), 1500 s (1.1 kG, 10 sccm, and 3 kW), and 4.0% (1.1 kG, 50 sccm, and 3 kW), respectively.

Sccm is an abbreviation for standard cubic centimeters per minute. In both gas species, $F$ and $I_{\text{sp}}$ increased with $P_{\text{RF}}$, whereas $F/P_{\text{RF}}$ decreased slightly with $P_{\text{RF}}$, especially in the case of xenon discharges, as shown in Fig. 3. Here, the maximum $I_{\text{sp}}$ was obtained with the smaller FR when $P_{\text{RF}}$ was large, and FR and $B$ had an optimum value of $P_{\text{RF}}$. The maximum $F$ and $F/P_{\text{RF}}$ were found to be larger in the case of xenon gas compared to argon. In addition, in the case of xenon gas, $F/P_{\text{RF}}$ showed a tendency to increase with increasing FR. On the other hand, the maximum $I_{\text{sp}}$ and $\eta$ were smaller in xenon as compared to argon.

The preceding parameters show excellent plasma performance even in the absence of active acceleration schemes. Needless to say, further improved plasma performance may be obtained for the target plasma under executed in the additional acceleration scheme.

Here, we compare our results of $F/P_{\text{RF}}$ with other helicon plasma thrusters. The characteristics of argon as a function of RF power are shown in Fig. 4, with the exception of two belonging to xenon (Nakamura et al. [13] (a), Ito et al. [14] (b), Tonoooka et al. [15] (c; i.e. = 50 mm, closed diamond; i.e. = 100 mm, open diamond), Shabschelowitz and Gallimore [16] (d), Takahashi et al. [11] (e), present results (f; Ar discharge, open squares; and Xe discharge, closed squares), Longmier et al. (g; VASIMR, VX-200; helicon and ICH, open circles [6]), and Longmier et al. (h; VASIMR, VX-200; Helicon and ICH, open circles [6]).
VX-200 helicon + ICH \[6\] (g) 20 100
Shabschelowitz and Gallimore [13] (a) 0.65 26 50 0.34 0.4
Nakamura et al. [15] (b) 0.52 30 230 3 1
Tonooka et al. [16] (c) 0.12 50 and 100 390 and 840 4 and 11 2
Shabschelowitz and Gallimore [16] (d) 0.55 90 330 11 1.5
Takahashi et al. [11] (e) 0.71 64 1500 11 1
Present results: Ar (f) 1.7 100 2000 21 3
Present results: Xe (f) 1.7 100 1500 40 3
VX-200 helicon + ICH [6] (g) 20 100–150 4900 5800 200
VX-200 helicon only [6] (h) 20 100–150 780 840 30

helicon only, closed circle \[6\]). Thrusters of \(a\) [13], \(b\) [14], and \(c\) [15] are permanent-magnet-type helicon thrusters, and those of \(d\) [16], \(e\) [11], and \(g, h\) [6] are electromagnet-type thrusters. The dotted line indicates a rough relationship between \(F/P_{RF}\) and \(P_{RF}\) in the case of \(a–f\), which represents the thrust class of less than a few kilowatts. On the other hand, \(g\) and \(h\) represent VASIMR VX-200 data, where \(g\) indicates characteristics of a helicon RF power of 28 kW with an ion cyclotron heating RF power of 0 to 172 kW, and \(h\) indicates those of a helicon RF power of 28 kW only. Other parameters of these thrusters are listed in Table 2. The thrust-to-power ratio increased with increasing RF power and/or increasing diameter of the discharge tube. Moreover, the source plasma in this study exhibited better performance in comparison to the kilowatt-class thruster.

### IV. Conclusions

Helicon plasma is very promising for future plasma thrusters owing to its electrodeless condition that increases the operational lifespan. To determine the thrust characteristics of a medium-sized, dense helicon plasma with a diameter of 100–170 mm, both argon and xenon helicon discharges were tested using an LMD without an additional acceleration method. The efficiency of the dense plasma was determined by deriving the thrust \(F\), the thrust-to-power ratio \(F/P_{RF}\), the specific impulse \(I_{SP}\), and the thrust efficiency \(\eta\) by using a target-type cylindrical thrust stand. In the case of argon gas, the maximum \(F\) and \(F/P_{RF}\) were 21 mN and 8.3 mN/kW, respectively. In the case of xenon gas, they were 40 mN and 16 mN/kW, respectively. When using xenon, the \(F/P_{RF}\) characteristics tended to increase with increasing RF.

A longer discharge tube may be necessary for future application involving additional electromagnetic acceleration application to the target plasma. In general, the long tube degrades the thrust performance by increasing wall loss. Therefore, a large-diameter discharge tube with a tapered section was used to reduce the wall loss, by considering a divergent magnetic field. The target plasma proposed in this study showed high performance in comparison with several kilowatt-class helicon plasma thrusters. Thus, an enlargement of the discharge tube diameter with a tapered inner surface to prevent the intersection of magnetic field lines produced by the electromagnets and the permanent magnets can be useful for promoting additional electromagnetic accelerations to target plasma.

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### References


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