# Studies on Plasma Production and Ion Heating by Using Only a Single Helical Antenna for a Simple Thruster[*)]

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Recently, studies of electric propulsion have been actively performed, and a new structure of radio frequency control has been proposed. The thrust of radio frequency driven electric propulsion is provided via plasma production and ion heating produced by excited wave of application of radio frequency. If the excited waves at the ion cyclotron resonance are left hand polarized, the waves couple to ions and ion heating takes place. On the other hand, the right hand polarized waves do not couple with ions and their energy goes to electrons via wave-particle interaction or direct acceleration. By employing a single helical antenna, the left hand polarized waves are launched toward one direction parallel to the magnetic field, and the right hand polarized waves are launched toward opposite direction simultaneously. Therefore plasma production and ion heating can be achieved by using only a single helical antenna. Basic experiments to examine the proposed structure have been performed, showing consistent results with expected scenario.

Keywords: plasma, plasma production, ion heating, ion acceleration, helical antenna, ion cyclotron resonance

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## 1. Introduction

Recently, space engineering is developing rapidly. Attention has been focused on an electric propulsion engine because it is suitable for a long-distance and long-term mission than chemical rockets. F.R. Chang-Diaz proposed the Variable Specific Impulse Magnetoplasma Rocket (VASIMR) engine, in which the thrust was provided via plasma production and ion heating [1]. The VASIMR engine has three major subsystems: a plasma generator stage, a radio frequency (RF) booster, and a nozzle [2]. The former two subsystems are almost duplicated in the sense because they use the same type of helical antennas and RF generators. Control of the thrust and the specific impulse is performed by changing the power to each subsystem. The plasma production and ion heating is produced by two helical antennas in VASIMR. This structure, however, needs two power supplying systems, and it makes the equipment larger and more complicated.

The authors proposed a more simple control method, in which a rotating electromagnetic field antenna was used [3]. This antenna consists of a pair of dual double half turn loops, which are so arranged that they are shifted spatially by $\pi/2$ in the azimuthal direction with respect to each other. By controlling relative phase difference between two loop currents, the fast wave that is suitable to produce high density plasma and the slow wave that accelerates ions via ion cyclotron resonance at the ion cyclotron resonance frequency are excited. So we can control thrust and specific impulse selectively by the phase control using a single antenna. This feature was experimentally demonstrated in a simulator of a plasma thruster.

The authors also proposed another simple control method that used a single helical antenna [4]. By using a right helical antenna, the slow wave in the direction of magnetic field can be excited, and the fast wave in the antidirection of magnetic field can also be excited. The same effects as those in the method by a pair of dual double half turn loop antenna can also be expected in this method. So, control of both plasma production and ion heating, and thus thrust and specific impulse can be achieved simultaneously by using a single helical antenna.

In the previous study of the method by a single helical antenna, pre-ionization plasma was needed to verify this idea experimentally as a lack of RF power of the equipment used. In this paper, we will present experimental verifications of the idea without pre-ionization plasma. We will demonstrate the start-up and the maintenance of the plasma by applying high RF power to a single helical antenna, and achieve plasma production and ion heating by using only one helical antenna without pre-ionization plasma. We will also examine the control of plasma production and ion heating by adjustment of magnetic field.

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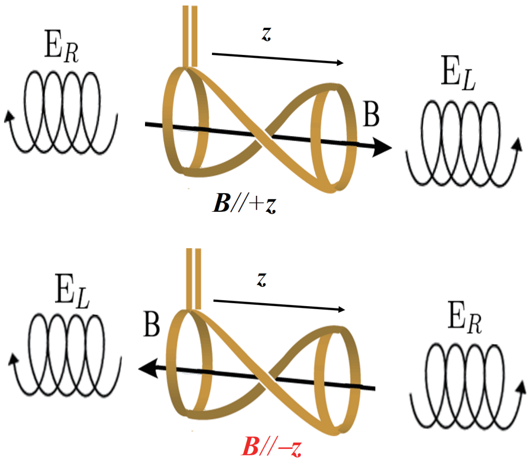

Fig. 1 Right helical antenna and excited waves.

## 2. Helical Antenna

The helical antenna is illustrated in Fig. 1. This right helical antenna 10 cm in diameter and 20 cm in length. 1.9-MHz RF Power (∼1 kW) is applied to the helical antenna.

The electromagnetic field of the azimuthal mode number $m$ of $+1$ excites the fast wave that is right-hand circularly polarized wave in the antidirection of magnetic field, and the field of $m$ of $-1$ excites the slow wave that is left-hand circularly polarized wave in the direction of magnetic field. Thus, both plasma production and ion heating can be achieved simultaneously by employing a single helical antenna, and by adjusting magnetic field, specific impulse can be controlled.

## 3. Experimental Device

Figure 2 shows the schematic diagram of our experimental device and the magnetic configuration lines. The device has a glass tube of 10 cm in diameter at the axial position $-50 < z < 0$ cm, and a metal chamber of 35 cm in diameter for $0 < z < 60$ cm. The magnetic field produced by the coil current $I_B$ is up to $B \sim 1.7$ kG. The feed gas is hydrogen. In plasma production measurement, hydrogen pressure is at 20 mTorr. In ion heating measurement, that is under gas puffing by using a piezo valve. The driving frequency of the helical antenna is $\omega/2\pi = 1.9$ MHz, and the ion cyclotron resonance is at $B = 1.24$ kG ($I_B \geq 220$ A). The RF power when measuring plasma production is 700 W, when measuring ion heating is 300 W. However, we don't measure the loss. Thus this RF power is apparent power. As shown in Fig. 2, a Langmuir probe (LP) is installed at $z = +18$ cm. In addition, a Faraday Cup (FC) that is movable along the $z$-axis is installed. The ion saturation current density $J_{\mathrm{is}}$ is measured by LP applying constant voltage −100 V. We use three-grid FC to measure energy distribution of ions. The voltage on the first grid is −100 V to repel electrons. The second grid is swept in voltage from −200 V to +600 V to repel ions with energies less than the grid voltage and pass those with energies higher. The voltage on the third grid is −100 V to suppress secondary electrons emitted by the ions hitting the collector. Voltage-current characteristic curves are obtained from the sweep voltage and the collector current relationship. The timing chart of the piezo valve, 1.9 MHz RF and sweep is shown in Fig. 3.

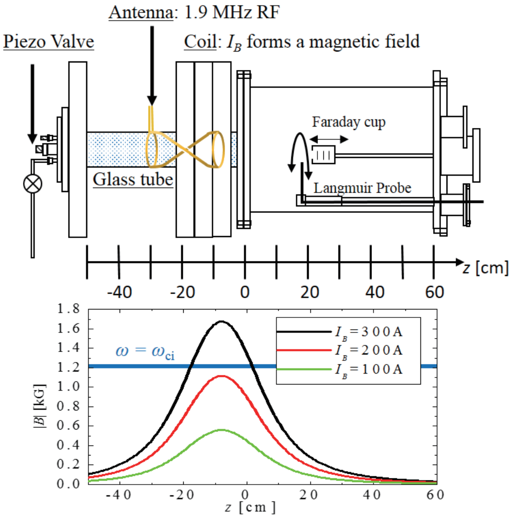

Fig. 2 Schematic of the experimental device and magnetic configurations.

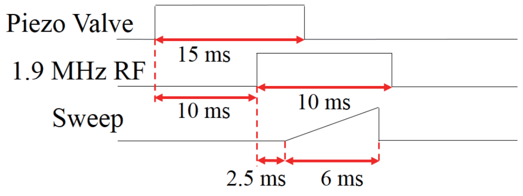

Fig. 3 Timing chart of piezo valve, 1.9-MHz RF and sweep.

## 4. Experimental Results

### 4.1 Plasma production

In the previous study, pre-ionization plasma was necessary to verify this idea experimentally due to a lack of power of RF with such a low frequency used. Therefore we used the base plasma that was produced by an application of RF power of 13.56 MHz to a double half turn antenna. The produced plasma flow into the helical antenna, and we demonstrated that $m = +1$ wave contributed plasma production. However, in this studies, we achieve the start-up and the maintenance of the plasma because we now use a plural-turn winding and higher RF power to a single helical antenna. Then, all results in this paper are obtained by using only a single helical antenna.

Figure 4 shows the time variation of $I_{\mathrm{is}}$ by LP, before and after switching on the RF for the magnetic field directed to the $+z$ direction (black line) and $-z$ direction (red line). The hydrogen pressure is 20 mTorr, and the 1.9-MHz

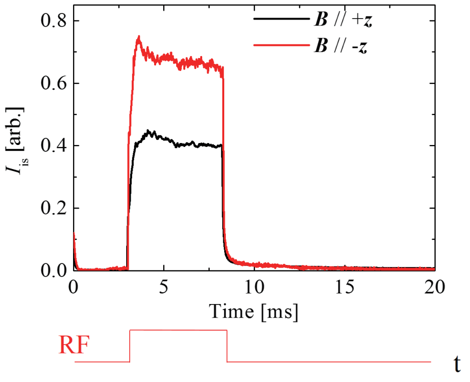

Fig. 4 Plasma start-up by 1.9-MHz RF.

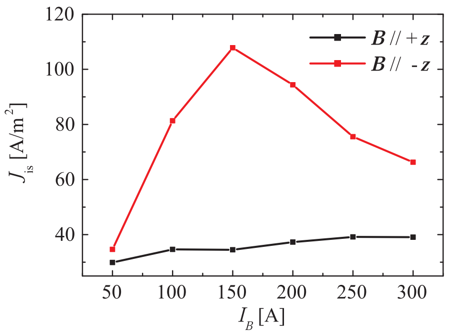

Fig. 6 Magnetic field dependence of plasma production.

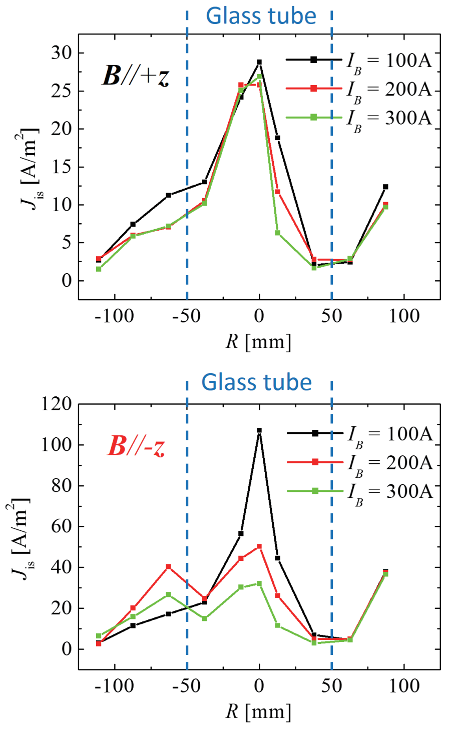

Fig. 5 Radial profile of the $J_{is}$.

RF is applied during 3 - 8 ms.

According to Fig. 4, while 1.9-MHz RF is applied to the helical antenna, the generation of $I_{is}$ is observed. Thus plasma production is accomplished by application of 1.9-MHz RF. It is found that when $B$ //$-z$, the saturated values of $I_{is}$ are larger than the case of $B$ //$+z$. This result appears that when $B$ //$-z$, right-handed circularly polarized wave is excited toward the location of the measurement as shown in Fig. 1 and plasma generation is performed. We consider that helicon wave plays the essential role in high-density plasma production.

We observe radial profile of $J_{is}$ for $B$ //$+z$ and $B$ //$-z$ at $z = +18$ cm, shown in Fig. 5. $J_{is}$ has the maximum value as the center of the glass tube. This radial profile appears to be caused by the electric fields $\boldsymbol{E}$ of $m = +1$ wave. In the present frequency range, $E_z$ of $m = +1$ wave can be neglected and $E_r$ and $E_\theta$ have a center peaked profile of Bessel function $J_0$ [5]. Since electrons were accelerated by $E_r$ and $E_\theta$, $J_{is}$ profile may have a shape of Bessel function $J_0$.

Experimental results of the magnetic field dependence are shown in Fig. 6. These results appear that $J_{is}$ of $B$ //$-z$ is dependent on $I_B$ than that of $B$ //$+z$.

We have shown in §3, helical antenna excites $m = -1$ wave in $z > 0$ for $B$ //$+z$. On the other hand, $m = +1$ wave is excited in $z > 0$ for $B$ //$-z$. In the experiment in this section, we obtained the results that $J_{is}$ in the case of $B$ //$-z$ is larger than in $B$ //$+z$ under the same experimental conditions except for the direction of magnetic direction. Thus we consider that the helicon wave that is excited by $m = +1$ wave contributes to high-density plasma production [6, 7].

## 4.2 Ion heating

The voltage-current characteristics are obtained by using the FC at $z = 10$ cm for $B$ //$+z$ with $I_B$ of 100 A and 220 A. Hydrogen pressure is under gas puffing by using the piezo valve. The ion energy distribution function (IEDF) $f(V_2)$ is obtained from

$$f(V_2) \propto \frac{1}{\sqrt{V_2 - V_S}} \frac{dI_C}{dV_2}, \quad (1)$$

where $I_C$ is the collector current and $V_2$ and $V_S$ are the second grid voltage and plasma potential, respectively. $V_S$ is obtained from floating potential and electron temperature measured by LP.

Figure 7 shows the ion energy distribution functions $f(V_2)$ for $I_B = 100$ and 220 A, where the data are taken for both the $B$ //$+z$ and $B$ //$-z$ cases. The distribution function for $I_B = 220$ A and $B$ //$+z$ shows the number of energetic ions increases at $V_2 \sim 80$ - 200 V and that of the thermal ions decreases around the local plasma potential ($V_2 \sim 50$ V). As already described and shown in Fig. 2, the magnetic field strength configuration for $I_B = 100$ A has no ion cyclotron resonance point, while the resonance can be seen at $z = -8$ cm for the $I_B = 220$ A case. These results appear to show that the energetic ions are produced by $m = -1$ wave via the ion cyclotron resonance heating

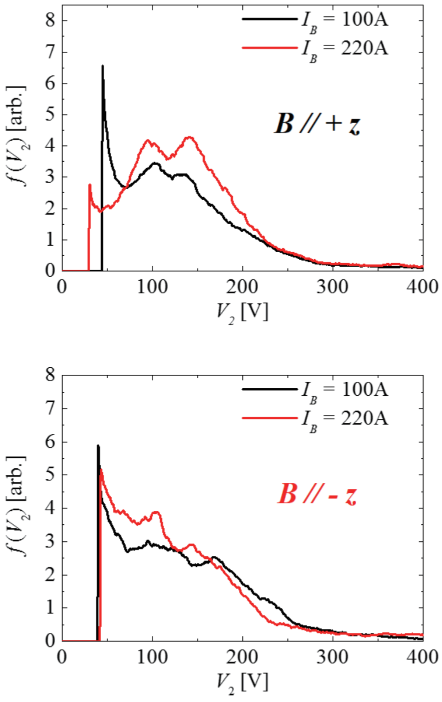

Fig. 7 The ion energy distribution function under gas puffing.

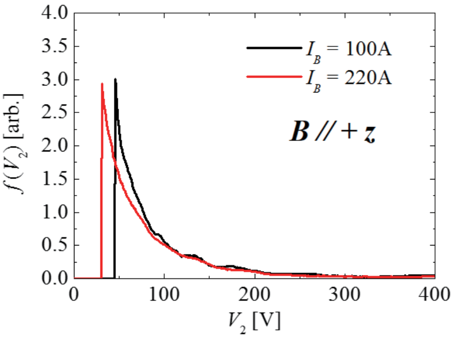

Fig. 8 The ion energy distribution function at 20 mTorr hydrogen pressure.

process.

On the other hand, when $B$ //$-z$, there is little difference of IEDF $f(V_2)$ at $I_B$ of 100 A and 220 A by comparison with $B$ //$+z$. Thus this result appears that ion heating was not performed because wave excited in $z > 0$ is not $m = -1$ but $m = +1$. Hence $m = -1$ wave play a major role in ion cyclotron resonance heating. Furthermore we can say that this ion acceleration is caused by not double layer acceleration but ion cyclotron resonance heating. Since it is considered that the double layer acceleration does not depend on the direction of magnetic field.

In addition, we observed the ion energy distribution function by FC at $z$ = 20 cm when $I_B$ is 100 A and 220 A at 20 mTorr hydrogen gas pressure, as shown in Fig. 8. Unlike Fig. 7, IEDF $f(V_2)$ does not shift toward larger energy and broaden. This result is caused by charge exchange. When hydrogen pressure is at 20 mTorr, neutral gas densities are much larger than the cases using the piezo valve. Therefore the ion is decelerated by charge exchange, and no significant difference in IEDF $f(V_2)$ between the cases of $I_B$ of 100 A and 220 A is found.

## 5. Summary

In order to examine a new scenario of RF control of plasma for electric propulsion using a single helical antenna, basic experiments have performed. When $B$ //$-z$, $I_{\mathrm{is}}$ is larger than the case of $B$ //$+z$. On the other hand, when $B$ //$+z$, IEDF $f(V_2)$ shifts toward larger energy at magnetic strength of ion cyclotron resonance. This results indicate that $m = +1$ wave is excited toward antidirection of magnetic field, $m = -1$ wave is excited toward direction magnetic field by using a right helical antenna. Using a single helical antenna, plasma production and ion heating is performed simultaneously. Thus helical antenna is effective to put a simple thruster into practice.

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