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Characteristics of rf-produced, high-density plasma with very small diameter

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To investigate characteristics of helicon plasma with a very small diameter, we have developed the Small Helicon Device (SHD) and measured the electron density under various conditions over a wide range of radio frequencies. Using a tube with inner diameter of 20 mm, an electron density n_e of ~ 10^{13} cm^{-3} near the antenna region was obtained with an excitation frequency f of 7 MHz, rf power P_{rf} of ~ 1000 W, and axial magnetic field in the magnet coil region B of 560 G. In the case of an inner diameter of 5 (10) mm under conditions of f = 12 (7) MHz, P_{rf} ~ 1000 W, and B = 280 G, n_e of ~ 10^{11} cm^{-3} was succesfully achieved even away from the antenna region.

KEYWORDS: Helicon Plasma, Electron Density, Small Helicon Device, Radio Frequency

1. Introduction

An electric propulsion system has a higher specific impulse than a chemical propulsion system, and it is suited for use on long-term missions. However, the operational lifetime of a conventional electric system, such as a Hall thruster, is limited by damage to electrodes resulting from direct contact with plasma. To solve this problem, we have proposed the electrodeless plasma propulsion system, using a high-density (~ 10^{13} cm^{-3}) helicon plasma.[1–4] In the case of producing a helicon plasma with a very small diameter of less than 20 mm, which is the smallest inner diameter (i.d.) achieved,[5, 6] this source will contribute to the development of a lightweight, small thruster such as an attitude control thruster. Alternatively, several units can be combined to provide greater thrust. The source may also have industrial applications, such as the coating of the inner wall of a thin tube.

In this paper, using the developed Small Helicon Device (SHD), we measured the electron density n_e while reducing the i.d. to 5 mm, to characterize the small-diameter helicon plasma. According to the dispersion relation of helicon plasma (Fig. 1[2]), if n_e and $k_{//}$ (parallel wavenumber) are kept constant, a smaller i.d. requires a higher radio frequency (rf) f and/or weaker magnetic field B.

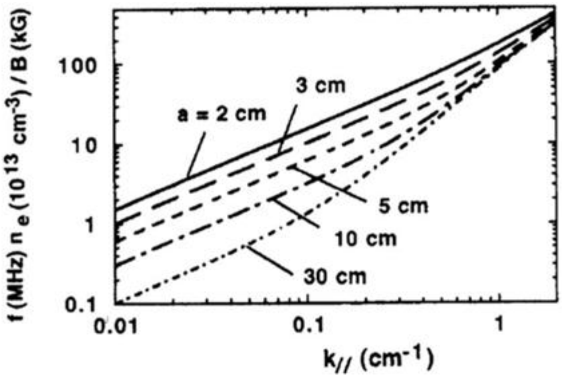
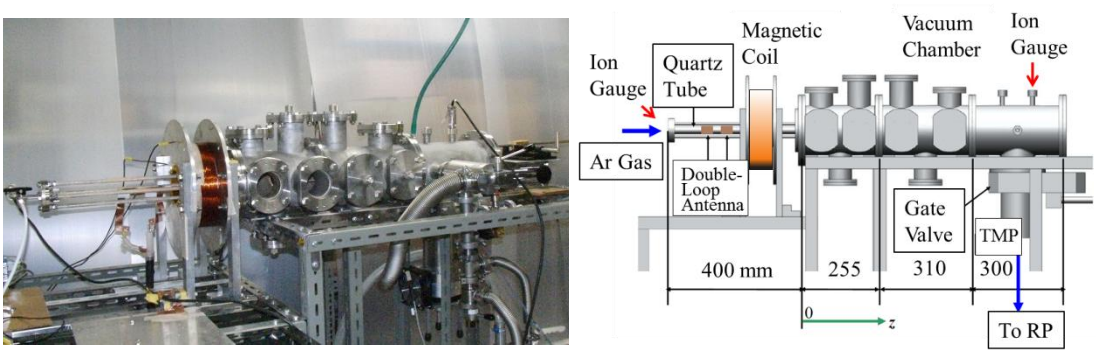


Fig. 1. Dispersion relation of helicon plasma.[2]

2. Experimental setup

The experiment employed the developed SHD, which is shown in Figs. 2 (a) and (b). A small quartz tube was connected to a vacuum chamber (SUS316) with diameter of 165 mm and axial length of 865 mm, pumped by an ULVAC CVD-050A rotary pump through an Osaka Vacuum TG200 turbo-molecular pump. Here, various diameter tubes can be connected to a gauge port adapter [left part of Figs. 2 (a) and (b)]. To measure the fill pressure, an ion gauge and a gas feeder were connected to an upstream flange. The base pressure in the vacuum chamber was ~ 7 × 10^{-5} Pa. We tested quartz tubes with i.d. of 5, 10 and 20 mm and axial length of 453 mm. The rf antenna had a double-loop made of copper plates with a thickness of 0.2 mm.



(a) (b)

Fig. 2. SHD: (a) photograph and (b) schematic drawing.

A T145-6326CK rf power source THAMWAY and T020-6326AK impedance matching box THAMWAY were used to generate ~1 kW rf power output for f = 7 and 12 MHz. For 50 and 70MHz excitations, a T162-6078C rf power source THAMWAY and T020-6078E matching box THAMWAY were used. Directional couplers inside the matching boxes were connected to a TDS 2024B oscilloscope Tektronix to measure rf power $P_{\rm rf}$ (the difference between the incident power and reflected power). Argon gas can be fed by a SEC-400MK3 unit HORIBA STEC at a flow rate (FR) from 0 to 30 sccm in steps of 0.1 sccm. To apply an external magnetic field, a handmade solenoidal coil (90 mm i.d., 360 mm outer diameter, 120 mm axial length and 400 turns) was used; the coil can produce an axial magnetic field of 28 G/A in the coil region.

To measure $n_{\rm e}$, a Langmuir probe and a Hioki 8855 Memory Hicorder data logger were used. The electron temperature, which is also needed to estimate $n_{\rm e}$, was assumed to be 3 eV (typical value).

3. Experimental results

Figure 3 shows n_e near the antenna region vs. $P_{\rm rf}$ at a FR of 20 sccm (~ 2.0 Pa in the source region) and i.d. of 20 mm. Figure 3(a) shows that n_e increased with $P_{\rm rf}$ under all rf frequencies of 7, 50 and 70 MHz, and was nearly the same with and without the field regardless of the rf power range. Although a density jump of a factor of ~ 100 to around 10^{13} cm^{-3} was observed for f = 7 MHz at $P_{\rm rf}$ ~ 700 W, n_e in the cases of 50 and 70 MHz excitations increased monotonically with $P_{\rm rf}$. The jump is considered to be a mode transition from Inductively Coupled Plasma (ICP) to helicon plasma.[7] In the case of f = 7 MHz and P_{rf} ~ 1000 W, n_{e} was lower in the presence of the magnetic field than without the magnetic field. This can be explained by the discharge of ICP being localized by a non-propagating wave and having higher input power density than the helicon plasma in the region near the antenna. Here, no stable discharge was observed for f = 7 MHz and no field when P_{rf} < 800 W.

In the case of f = 70 MHz, n_e was higher than that for f = 50 MHz when P_{rf} < 150 W. However, n_e in the 70 MHz case was saturated at P_{rf} > 150 W, whereas it continuously increased with P_{rf} in the 50 MHz case. Figure 3(b) (f = 50 and 70 MHz) shows a low density (~ 10^8 cm^{-3}) for very low rf power of ~ 1 W, and density jumps of a factor of ~ 100 were observed at ~ 8 W for f = 50 MHz and 2 W for f = 70 MHz, which can be considered as mode transitions from Capacitively Coupled Plasma (CCP) to ICP.

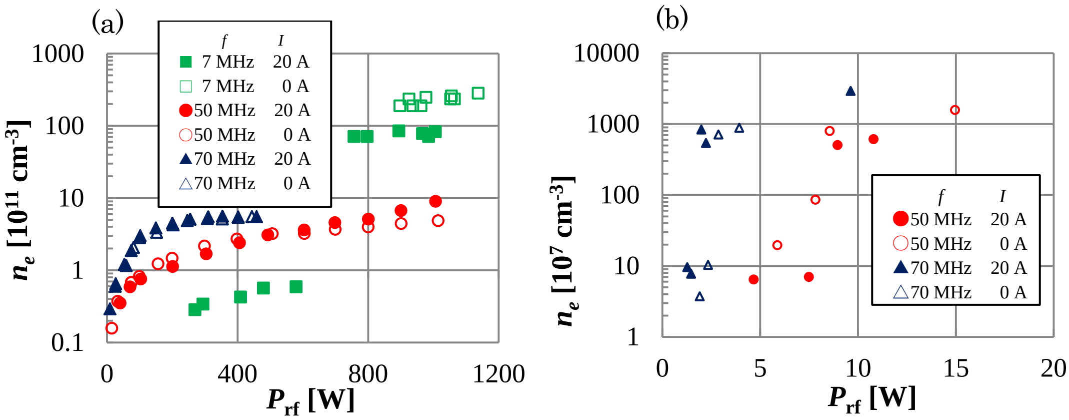


Fig. 3. n_e (under rf antenna) vs. P_{rf} for 20 mm i.d., changing f and the magnetic coil current I: (a) 0 – 1200 W and (b) 0 – 20 W.

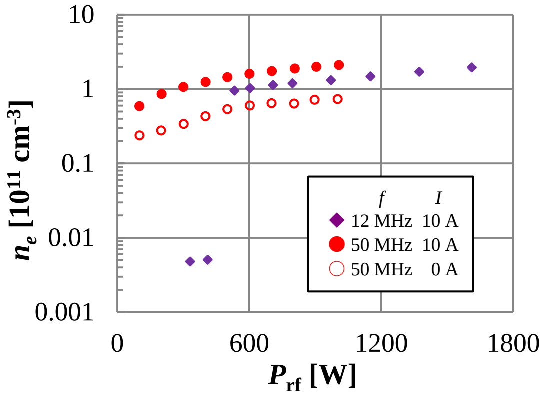


Fig. 4. n_e (z = 65 mm) vs. P_{rf} for 10 mm i.d., changing f and I.

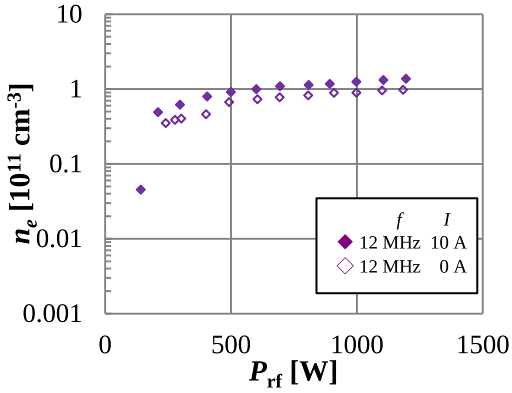


Fig. 5. n_e (z = 65 mm) vs. P_{rf} for 5 mm i.d., changing I.

Figures 4 and 5 show n_e at z = 65 mm (in the vacuum chamber region) vs. P_{rf} for an FR of 5 sccm (~ 1.6 Pa in the source region) and i.d. of 10 and 5 mm, respectively. Because n_{e} was measured away from the antenna region in these figures, higher density can be expected near the source region. Although plasma was initiated with P_{rf} < 100 W in the case of an i.d. of 5 mm, no plasma plume reached the vacuum chamber, and n_e was too low to be measured in the vacuum chamber region. Because the diameter of a

Langmuir probe tip is a relatively large fraction of that of the quartz tube, the probe disturbed discharges, which demonstrates a difficulty in estimating n_e in the quartz tube region. However, at z = – 40 mm (i.e., in the source region), n_e could be measured as ~ 10^{12} cm^{-3} for an i.d. of 10 mm, P_{rf} ~ 1000 W and f = 12 MHz. Considering stable discharges, we used f = 12 MHz instead of f = 7 MHz for both diameters. In addition, in the case of an i.d. of 5 mm, plasma discharges for f = 50 and 70 MHz were too unstable to estimate n_e.

No density jumps were observed for f = 50 MHz and an i.d. of 10 mm, regardless of the strength of the magnetic field, when maintaining high n_e in a low P_{rf} region. In the case of f = 12 MHz, n_e before the density jump was lower than that for f = 50 MHz, but after the jump, n_e (~ 10^{12} cm^{-3}) was similar to that in the case of f = 12 MHz.

Recently, we succeeded in generating relatively high density plasma discharges with 5 mm i.d., and n_e ~ 10^{11} cm^{-3} was obtained at z = 65 mm even away from the source region with P_{rf} = 1000 W from Fig. 5. Without the magnetic field, using tubes with an i.d. of 5 and 10 mm, n_e did not change appreciably from that in the case with the field (Figs. 4 and 5).

4. Conclusion

We have developed an SHD and produced a high-density (up to 10^{13} cm^{-3}) plasma with very small diameter (down to 5 mm). In the present study, the rf plasma characteristics for i.d. of 5, 10 and 20 mm were investigated with f = 7, 12, 50 and 70 MHz.

At higher f of 50 and 70 MHz, there was no clear density jump; however, the plasma could be produced with very low rf power of ~ 1 W. We also produced high-density plasmas with the smallest i.d. of 5 mm.

However, we could not measure n_e in the quartz tube region with an i.d. of 5 or 10 mm because of the probe disturbing the plasma. Discharge modes such as CCP, ICP and helicon plasma must be verified by measuring wave structures directly in future work.

We plan to use a thinner quartz tube and to extend the frequency range, mass flow rate, and magnetic configuration. Useful non-contact diagnostics will be a magnetic probe array measurement outside the quartz tube for observing wave propagation of helicon plasma, spectroscopy, laser-induced fluorescence and microwave interferometry methods.[8]

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