Hydrogen Plasma Production in the Lower-Hybrid Frequency Range

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Abstract

Hydrogen plasmas are produced by using the radio frequency (rf) discharge. Plasma density $n_p$ depends strongly on the strength of the external magnetic field $B_0$ and has a peak when $B_0$ and the frequency satisfy the lower-hybrid resonance condition. Various types of antennas are used, and the helical antenna gives the maximum $n_p$ of $5 \times 10^{12} \text{ cm}^{-3}$ at 3.5 kW and 200 G.

Keywords:
hydrogen plasma, lower hybrid resonance, antenna configuration, loop antenna, helical antenna

1. Introduction

Compact high-density hydrogen beam sources are useful for measuring local ion and electron temperatures and densities in nuclear fusion research. Plasma production by using wave electric field in the frequency range of $\omega_{ci} < \omega < \omega_{ce}$ is known as a helicon-wave discharge. Helicon-wave plasma sources are attractive because they can produce high-density plasmas at relatively low gas pressure of a few mTorr [1-3]. However, when hydrogen gas is used, plasma density is low compared with rare-gas plasmas [4]. Our purpose is to develop a compact high-density hydrogen-plasma source by using radio frequency (rf) discharges. In this study, plasma production near the lower-hybrid resonance condition is investigated. Various types of antennas are used and optimization of antenna structure is conducted.

2. Experimental Setup

The experiment is conducted in a linear device shown in Fig. 1. A vacuum chamber is made of stainless steal (inner diameter is 36.5 cm and length is 150 cm). A Pyrex tube with inner diameter of 5 cm and length of 90 cm is connected to one end of the vacuum chamber.

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z = 3 cm. Here. z = 0 is the position of the antenna edge. The electron temperature T_e is measured by the probe at z = 40 cm, which accomplishes an rf compensation [5].

3. Antenna Configurations

Figure 2 shows three types of antennas that are used to examine efficiency of hydrogen plasma production. All antennas are made of a copper strip. One is the helix type [Fig. 2(a)], in which the rf current flows with a pitch angle \( \theta \) with respect to \( B_0 \). The copper strip is wound along the Pyrex tube and its length on the surface of the tube is kept constant with 11 cm. When \( \theta = 0 \), the antenna is identical to Nagoya type III antenna [6], and induces the rf electric field parallel to \( B_0, E_z \), in vacuum. As \( \theta \) increases, both \( E_z \) and the azimuthal component of the electric field \( E_\theta \) are induced. When \( \theta = 90^\circ \), the antenna is nearly a half-turn loop antenna. The antenna induces mainly \( E_\theta \), and \( E_z \) in vacuum vanishes. In Fig. 2(b) a two-turn loop antenna is shown. \( L \) and \( W \) are defined as the distance between two antenna loops and width of antenna strip, respectively. Figure 2(c) shows a helical type antenna, in which the length along \( B_0 \) and the helical pitch is 20 cm and 23\(^\circ\), respectively. This antenna induces both \( E_\theta \) and \( E_z \) components.

4. Results

The variation of \( n_p \) as a function of \( P_{rf} \) for \( B_0 = 0 \) and 200 G with the two-turn loop antenna (\( L = 0 \) cm and \( W = 1 \) cm) and for \( B_0 = 150 \) G with the one-turn loop antenna (\( W = 1 \) cm) is shown in Fig. 3(a). Density jumps, which mean discontinuous increase in \( n_p \) as \( P_{rf} \) increases, occur at 500 W and 1.5 kW when \( B_0 = 0 \) and 200 G, respectively. We define the discharge modes before and after the density jump as the low-density (LD) mode and the high-density (HD) mode, respectively. When \( B_0 = 0 \) G, in the LD mode the plasma production is done by the electric field due to the antenna voltage \( V_{rf} \) (E discharge), on the other hand, in the HD mode plasma is produced by the electric field due to the antenna current \( I_0 \) (H discharge) [7]. When \( B_0 = 200 \) G, even though the threshold \( P_{rf} \) is larger than that for \( B_0 = 0 \) G, the density jump corresponds to the transition from E to H discharge. In the LD mode, \( n_p \) for the one-turn loop antenna is smaller than that for the two-turn loop antenna because of the smaller \( V_{rf} \) due to its lower inductance. When the one-turn loop antenna is used, the density jump or the transition from E to H discharge does not occur. This is because the induction field for the one-turn loop antenna is half of that for the two-turn one.

Fig. 2 Antenna configurations. (a) Helix antenna, (b) two-turn loop antenna and (c) helical antenna.

Fig. 3 (a) Dependence of \( n_p \) on \( P_{rf} \) with and without \( B_0 \) using the two-turn (\( L = 0 \) cm and \( W = 1 \) cm) and one-turn loop antennas (\( W = 1 \) cm). (b) Plasma density \( n_p \) versus \( B_0 \) using the two-turn loop antenna (\( L = 0 \) cm and \( W = 1 \) cm) at the HD mode (\( P_{rf} = 3 \) kW).
Figure 3(b) shows the dependence of \( n_p \) on \( B_0 \) for the two-turn loop antenna at the HD mode (\( P_{RF} = 3 \) kW). \( n_p \) peaks around 200 G, where the lower-hybrid resonance condition \( \omega = \omega_{lh} \) is satisfied. Here, \( \omega_{lh} \) is defined by the following equation,

\[
\omega_{lh}^{2} = \omega_{ce}^{2} \left( \frac{\omega_{pe}^{2} + \omega_{ci}^{2}}{\omega_{pe}^{2} + \omega_{ci}^{2}} \right),
\]

(1)

where \( \omega_{ce} \) and \( \omega_{ci} \) are the electron and ion cyclotron frequencies, respectively, and \( \omega_{pe} \) is the electron plasma frequency. At the high-density limit of \( \omega_{pe}^{2} \gg \omega_{ci}^{2} \gg \omega_{ce} \omega_{ci} \), \( \omega_{lh} \) is given by

\[
\omega_{lh-HD} = \sqrt{\omega_{ce}^{2} \omega_{ci}^{2}}.
\]

Nearly two times larger \( n_p \) at \( B_0 = 200 \) G than that at \( B_0 = 0 \) G is caused by the contribution of the high-efficient plasma production at the lower hybrid resonance in addition to H discharge.

The dependence of \( n_p \) on \( B_0 \) is measured as a function of \( f \) using the two-turn loop antenna (\( L = 10 \) cm and \( W = 3 \) cm) at the HD mode \( P_{RF} = 1 \) kW. When \( f \) is varied, \( n_p \) peaks at different values of \( B_0 \) that satisfy the lower-hybrid resonance condition, and reaches \( n_p \approx 6 \times 10^{11} \) cm\(^{-3} \). Figure 4 shows \( B_p \) at the peak of \( n_p, B_p \), versus \( f \). The calculated \( B_0 \) that satisfies \( \omega = \omega_{lh-HD} \), \( B_{lh-HD} \), is also shown. The measured \( B_p \) shows similar \( f \) dependence to \( B_{lh-HD} \). The difference between \( B_p \) and \( B_{lh-HD} \) can be explained by considering the contribution of the plasma density shown in eq. (1).

The plasma density \( n_p \) versus \( B_0 \) for \( \theta = 0^\circ, 27^\circ \) and \( 90^\circ \) of the helix antennas at \( P_{RF} = 3 \) kW is shown in Fig. 5(a). When \( \theta = 27^\circ \), \( n_p \) peaks strongly near the lower hybrid resonance and the discharge is in the HD mode. While when \( \theta = 0^\circ \), the density peak around the lower hybrid resonance is not observed. When \( \theta = 90^\circ \), the discharge is in the LD mode because of low induction field.

Figure 5(b) shows \( n_p \) at \( B_0 = 200 \) G, i.e., near the lower-hybrid resonance condition, as a function of \( \theta \). The plasma density \( n_p \) peaks at \( \theta = 45^\circ \). When \( \theta > 70^\circ \), \( n_p \) values are small and the discharges are in the LD mode.

The dependence of \( n_p \) on \( B_0 \) at the HD mode (\( P_{RF} = 3.5 \) kW) with the helical antenna, which has the both \( E_z \) and \( E_p \) [see Fig. 2(b)], is shown in Fig. 6. The maximum density of \( 5 \times 10^{12} \) cm\(^{-3} \) is achieved at 200 G. Furthermore, \( n_p > 1.6 \times 10^{12} \) cm\(^{-3} \) is obtained in a wide \( B_0 \) range of \( B_0 = 100 - 900 \) G.
5. Discussion

The dispersion relation of electromagnetic waves in a uniform plasma is expressed as [8]

\[
Sn^4 + [n^2_\perp (S + P) - (RL + PS)n^2_\parallel] + P(n^2_\parallel - R)(n^2_\perp - L) = 0,
\]

(3)

where \(n_\perp = ck_\perp/\omega\), \(n_\parallel = ck_\parallel/\omega\), \(c\) is the speed of light, and \(k_\perp\) (\(k_\parallel\)) is the wave number perpendicular (parallel) to \(B_0\), respectively. \(R\), \(L\), \(P\), \(S\) and \(D\) are the dielectric tensor elements [8]. When \(\omega_0 \ll \omega \ll \omega_{pe}\), two branches exist; one is the slow waves and the other is the fast waves (helicon waves) [4]. The slow and fast waves exist in the low-density and high-density regions, respectively. When \(B_0 < B_{lH-HD}\), the slow and fast waves merge each other at \(N^2_z = 4S\). On the other hand, when \(B_0 > B_{lH-HD}\) the slow waves satisfy the lower hybrid resonance at \(S = 0\). In the density region below \(10^{12}\) cm\(^{-3}\), it is difficult to excite the helicon waves since the axial wavelength becomes too long compared with the plasma length. Therefore, enhancement of \(n_p\) at the lower hybrid resonance in this density region might be caused by the slow waves.

Near the lower hybrid resonance, the dispersion relation of the slow waves is identical to that of the cold electrostatic waves, and the slow waves propagate almost perpendicular to \(B_0\) in the radial direction [4]. Therefore, as approaching to the resonance the radial component of the electric field \(E_r\) becomes large. In order to make the antenna field couple effectively to the waves near the resonance, antennas producing large \(E_r\) should be used. Therefore, it seems that \(\theta = 0^\circ\) antenna which induces large \(E_r\) in vacuum is not appropriate to excite the wave electric field near the resonance and no enhancement of \(n_p\) occurs as shown in Fig. 5(a). If the loop antennas having \(E_\theta\) component are used, the production of the space charge is possible due to the radial motion of electrons caused by \(E_\theta \times B_0\) drift. The resultant radial electrostatic fields couple to the slow waves near the lower hybrid resonance as shown in Figs. 3(b) and 4.

When the helical antenna is used, the maximum \(n_p\) of \(5 \times 10^{12}\) cm\(^{-3}\) is achieved at \(B_0 = 200\) G, and \(n_p > 1.6 \times 10^{12}\) cm\(^{-3}\) is obtained for \(B_0 = 100 \sim 900\) G. According to the results shown in Figs. 5 and 6, the antennas having both \(E_\theta\) and \(E_r\) such as the 27° antenna and the helical antenna, are effective to produce high-density hydrogen plasmas. Especially, the helical antenna is suitable to excite the helicon waves with azimuthal mode \(m = +1\) [3]. Therefore, it is likely that the helicon waves start to contribute to the plasma production in this density region in addition to that of the slow waves.

In order to clarify the contribution of waves on the plasma production, we are planning to measure the wave magnetic field using a magnetic probe.

6. Conclusion

Hydrogen-plasma production using the rf discharge in the frequency range of \(\omega_0 \ll \omega \ll \omega_{pe}\) is investigated. Plasma density \(n_p\) peaks when \(B_0\) satisfies the lower-hybrid resonance condition. The dependence of \(n_p\) on the pitch angle (\(\theta\)) is measured using the helix type antennas. \(E_z\) and \(E_\theta\) are necessary for efficient hydrogen plasma production. The maximum values of \(n_p\) obtained at 3.5 kW are \(5 \times 10^{12}\) cm\(^{-3}\) for the helical antenna, 1.7 \(\times 10^{12}\) cm\(^{-3}\) for the two-turn loop antenna and 7 \(\times 10^{11}\) cm\(^{-3}\) for the helix antenna.

References