Frequency dependent effects of helicon plasmas near the lower hybrid resonance

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The analytic solution of the wave equation is used to investigate the eigenmode characteristics of helicon plasmas near the lower hybrid resonance. It is shown that there are innumerable or a few isolated eigenmodes depending on the value of the wave frequency whether it is higher or not than that of the lower hybrid frequency. The plasma resistance is usually large with a sharp peak near the lower hybrid frequency, but it depends on the plasma density. Accordingly, a self-consistent simulation is carried out using the solutions of the wave equation and the global balance equations. The numerical results reveal that there exists a threshold frequency for a steep change in the electron density near the lower hybrid resonance.

I. INTRODUCTION

Since its introduction by Boswell [1], helicon plasma has been of considerable interests because of high ionization efficiency. The typical operating frequency of helicon plasmas is between the lower hybrid frequency and the electron cyclotron frequency, but there have been several experimental studies suggesting that the optimal frequency of helicon discharge is related to the lower hybrid resonance. Zhu and Boswell observed the maximum optical gain of the spontaneous emission near the lower hybrid resonance [2], and recently Yun *et al.* reported that the maximum densities were achieved when the wave frequencies were close to the lower hybrid frequencies [3,4]. In addition, abrupt density jumps were found to occur near the lower hybrid frequency when the wave frequency is varied [5].

Transport of the rf energy to plasmas using the lower hybrid waves has been extensively studied for heating of fusion plasmas in Tokamaks, but the role of the lower hybrid resonance in helicon plasmas has not been examined in detail yet. In this work, the eigenmode characteristics are investigated for the various values of the wave frequency and the magnetic field to explain the frequency dependence of helicon plasmas near the lower hybrid resonance. In addition, a self-consistent numerical simulation for the electron density is carried out as the eigenmode condition depends on the density. The numerical results are then used to show that there exists a transition or threshold frequency for efficient ionization near the lower hybrid resonance.

II. LOWER HYBRID AND EIGENMODE RESONANCES

The propagation of electromagnetic waves in helicon plasmas is governed by the Maxwell equations. Considering the boundary conditions at the end plates, the components of the electromagnetic field are expanded in sine or cosine series, $e^{im\theta}\sin(k_n z)$ or $e^{im\theta}\sin(k_n z)$, where $k_n = n\pi/L$ and L is the length of the chamber, and m and n

are integers. For a uniform plasma, the electromagnetic field is expressed in terms of Bessel functions whose argument is $p\rho$; the perpendicular wave number p is the root of the biquadratic equation $p^4 - (\alpha + \beta)p^2 + \alpha\beta - \gamma\delta = 0$, where $\alpha = \epsilon_1 - N^2 - \epsilon_2^2/\epsilon_1$, $\beta = \epsilon_3 (1 - N^2/\epsilon_1)$, $\gamma = N\epsilon_2\epsilon_3/\epsilon_1$, $\delta = N\epsilon_2/\epsilon_1$, $N = k_n c/\omega$, and the ϵ's are components of the cold plasma dielectric tensor [6]. The perpendicular wave number for the slow TG wave becomes infinite for collisionless plasmas when the condition for $\epsilon_1 = 0$ or $\omega = \omega_{\rm LH}$, $\omega_{\rm UH}$ is satisfied, where $\omega_{\rm LH}$ and $\omega_{\rm UH}$ are the lower and upper hybrid frequencies, respectively.

When the electromagnetic field is generated by an external source in bounded plasmas, there is another kind of resonance called the coupling resonance that occurs when the launched wave matches one of the eigenmodes of bounded plasmas. The condition for an eigenmode to exist can be given as [6]

$$D_g(m, n, \omega, n_e, B_0, r_p, r_a, r_b, L) = 0 \tag{1}$$

where ω, n_e, B_0, r_p, r_a, and r_b are the wave frequency, the electron density, the external magnetic field, the plasma boundary radius, the radial antenna location, and the conducting boundary radius, respectively.

In the presence of collisions the field strength is locally maximum when the eigenmode condition is satisfied, as the determinant D_g appears in the denominator of the coefficients for the field excited by an external current source. This behavior of the field is reflected on the plasma resistance R_p. In practice, the rf power can be dissipated in the plasma and the other part of the device so that the net power absorption by the plasma may be approximated by $P_{\rm abs} = P_{\rm rf} R_{\rm p}/(R_{\rm p} + R_{\rm c})$ where $P_{\rm rf}$ is the rf power delivered from the power supply and $R_{\rm c}$ is the circuit resistance [7].

III. NUMERICAL RESULTS

For illustration, numerical calculation is done for the following parameters unless otherwise specified: $L = 80$ cm, $r_p = 5$ cm, $r_a = 6$ cm, $r_b = 10$ cm, and $R_c = 0.5\ \Omega$. The electron collision frequency ν_e is taken to be 10 MHz and the ion collision frequency is neglected. The Nagoya type III antenna is used and supposed to be at the center of the chamber, and the conducting plates are assumed to be located at the ends of the chamber as in the previous work [6]. Modes with $m = -11, \cdots, 11$ and $n = 1, \cdots, 50$ are taken into account in calculating the total resistance.

The magnitude of D_g is presented in Fig. 1 where the existence of an eigenmode is denoted by a sharp depression for a very small but finite value of the collision frequency. The figure shows that there are innumerable eigenmodes between the mode coupling point and the lower hybrid resonance, but there are a few isolated eigenmodes for frequencies lower than the lower hybrid frequency.

The plasma resistance is presented as a function of the frequency at a given magnetic field in Fig. 2. It is small for frequencies lower than $\omega_{\rm LH}$ and has a peak near $\omega_{\rm LH}$ for the densities exceeding a certain value. Therefore, when the resistance approaches the peaked value near the lower hybrid resonance, as the frequency is increased, the power absorption efficiency is considerably enhanced to result in a higher value of the electron density. Since the magnitude as well as the peak location of the resistance depends on the plasma density itself, however, a self-consistent procedure should be used to obtain a legitimate conclusion.

The wave equation is solved self-consistently with the global balance equations for the electron density and temperature and the neutral density [8]. The results of numerical simulations are presented in Fig. 3 showing that there exists a transition or threshold frequency $\omega_{\rm th}$ for efficient discharge at a given magnetic field. For $\omega < \omega_{\rm th}$, the density is low and varies rapidly as the frequency does. The density abruptly jumps up as the frequency is increased to approach the threshold frequency, and then it does not change as much as in the case of $\omega < \omega_{\rm th}$, thereafter. These threshold frequencies, which are approximately 3.6, 5.4, 7.2, and 9.0 MHz, are close to the lower hybrid frequencies 3.1, 5.1, 7.1 MHz, and 9.1 MHz for the case of 300, 500, 700G, and 900 G, respectively, at the density of 2×10^{12} cm^{-3}. Figure 4 shows that the density increases overall but the threshold frequency virtually remains constant as the rf power is increased.

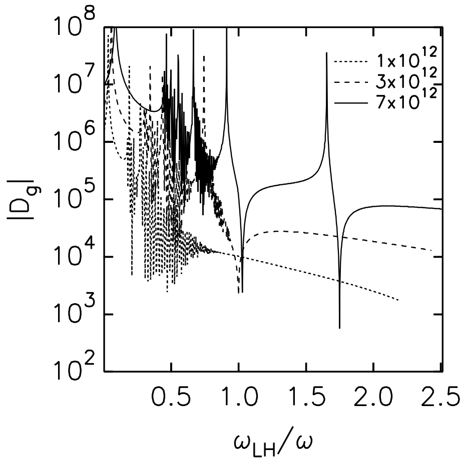

FIG. 1. The magnitude of D_g is presented as a function of the magnetic field for different densities (m=1, n=2, $\omega/2\pi$=8 MHz, and ν_e/ω=10^{-3}). The magnetic field is varied up to 2000 G.

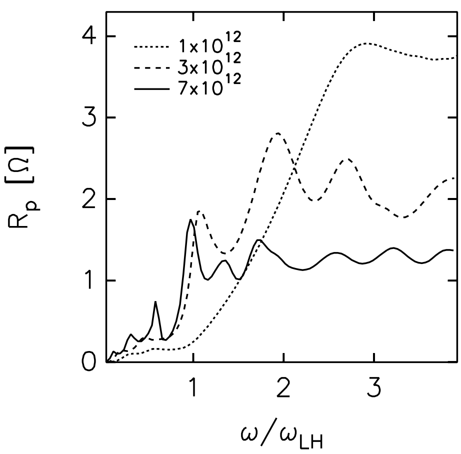

FIG. 2. The plasma resistance is plotted as the function of the wave frequency, which is varied up to 20 MHz, at the fixed magnetic field of 500 G for different densities.

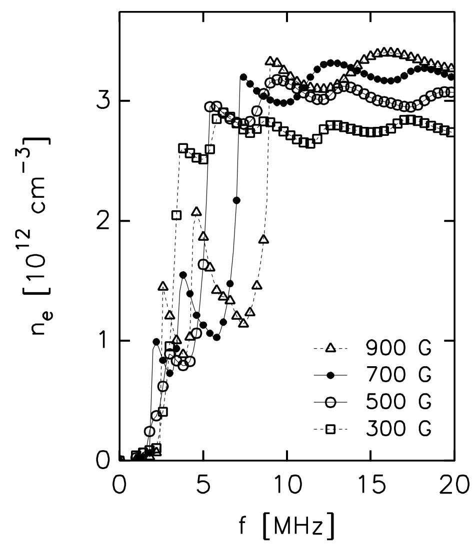

FIG. 3. The electron density n_e is given as a function of the frequency for the different values of the magnetic field with $P_{\rm rf}$=300 W.

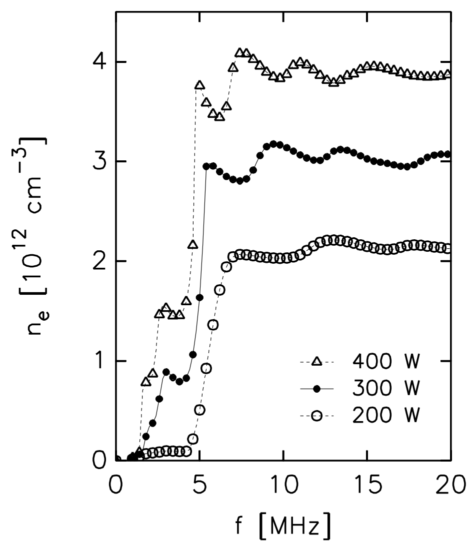

FIG. 4. The electron density is given as a function of the frequency for the different values of the rf power at B_0=500 G.

The experimental results of Yun *et al.* [3] show that there exist optimum frequencies for high density discharges near the lower hybrid frequencies. Their optimum frequency appears to be the threshold frequency of this work, but the variation of the density measured is different from that presented in Fig. 3. On the other hand, the density variations measured by Kwak *et al.* are quite similar to the computed ones. This seems to be due to the fact that Yun *et al.* measured the densities at a particular radial position while Kwak *et al.* did the line-averaged densities by a microwave interferometer. Since the density profile changes near the lower hybrid frequency [4], the density at a particular position does not vary in proportion to the average density as the frequency or the magnetic field is varied across the lower hybrid resonance. The variation of the average density is more consistent with the global model, which assumes the uniform density profile, than that of the local density.

IV. CONCLUSIONS

It is shown that there are innumerable or a few isolated eigenmodes depending on the value of the wave frequency whether it is higher or not than the lower hybrid frequency. Consequently, the resistance peaks constitute the overall resistance that is quite large in the wide range of the frequency being higher than the lower hybrid frequency, but there appear a few isolated small peaks of the resistance for lower frequencies at a given magnetic field. The resistance is usually large with a sharp peak near the lower hybrid frequency, but both magnitude and location of the resistance peak depend on the plasma density. Therefore, numerical simulations are carried out self-consistently using the solutions of the wave equation and the global balance equations. The results show that there exist a threshold frequency near the lower hybrid resonance at a given magnetic field. For frequencies lower than the threshold frequency, the density is low and changes rapidly as the frequency is varied, and then it abruptly jumps up as the frequency is increased to approach the threshold frequency.

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