Jpn. J. Appl. Phys. Vol. 38 (1999) pp. L 148–L 150
Part 1, No. 2A, February 1999

Role of Electron Thermal Motion in Evanescent Electromagnetic Wave Structure of Inductively Coupled Plasma

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(Received November 30, 1998; accepted for publication December 15, 1998)

The role of electron thermal motion in radio-frequency (RF) plasma produced by a planar, spiral antenna was examined. The measured evanescent wave amplitude and the phase were compared to the calculated results obtained from a one-dimensional collisionless (nonlocal) model, changing the boundary condition, Ar filling pressure and RF frequency. It was demonstrated that electron thermal motion plays a more important role under the condition of low collisionality.

KEYWORDS: RF plasma, ICP, spiral antenna, evanescent wave, antenna-plasma loading resistance, collisionality, electron thermal motion, nonlocal model, resonant coupling

Inductively coupled plasma/transformer coupled plasma (ICP/TCP)[1,2] have been recognized as high-density plasma sources in the radio-frequency (RF) range, which are needed for plasma processing and confinement devices. Theoretical and experimental characterization and optimum plasma production have been attempted. For the electron heating mechanism in the ICP, especially under low collisionality, collisionless heating owing to electron thermal motion was proposed theoretically, i.e., the anomalous skin effect.[3] This was further clarified by the simulation recently performed by Turner.[4] In our previous work,[5,6] the role of electron motion in ICP produced by a spiral antenna was investigated by measuring the skin depth of an evanescent wave and antenna-plasma resistance in a wide range of collision frequencies. For ICP production, the dominant role of the collisionless (collisional) heating mechanism under low (high) collisionality was demonstrated. In addition, under low collisionality, a unique pattern of the wave field in this experimental configuration was observed for the first time.[6] This pattern was not predicted using the cold plasma theory, but could be expected considering the effect of electron thermal motion.[7] Moreover, the minimum amplitude of the evanescent wave was considered to reflect the optimum chamber length related to resonant coupling between the field and the electron bounce motion from the effective boundaries under low collisionality.[7]

In this letter, we report the effect of electron thermal motion in an ICP produced by the spiral antenna. The amplitude and phase of the evanescent electromagnetic wave fields and antenna-plasma loading resistance were measured, and they were compared with the values calculated using the one-dimensional model described in ref. 7. A similar experiment to this wave pattern was performed after the publication of our previous study[6] for a fixed boundary and varying RF power.[8] The present study is the first trial of wave pattern measurement with various boundary conditions, Ar filling pressures and RF frequencies, and it demonstrates that electron thermal motion plays a more important role for ICP production under low collisionality.

The experimental system was similar to the one in ref. 5 except for the lack of the external magnetic field. The four-turn, water-cooled, spiral antenna with a diameter of 18 cm was made of copper. The distance between the surface of the antenna and the quartz window, which was 25 cm in diameter and 0.8 cm thick, was 1.7 cm. Here, $z = 0$ cm was defined as at the window surface which faces the inner vacuum chamber ~45 cm in diameter and 170 cm in length. In this experiment, a movable end plate made of stainless steel with a diameter of 38 cm was inserted axially from the end of the chamber. Here, the end plate was regarded as a virtual boundary at $z = L$. The RF input power was ~300 W with a frequency f of 7 MHz. Ar plasma parameters on axis were measured using movable Langmuir (1 mm in diameter with 3 mm length) and magnetic (axial component B_z: one turn coil with 7 mm in diameter) probes inserted axially into the plasma.

Figure 1(2) shows the (a) axial profile of the measured amplitude (phase) of the excited magnetic field B_z and (b) one-dimensional profile of the amplitude (phase) calculated using the measured electron density n_e and electron temperature T_e near the antenna, at the argon pressures $P = 0.65$, 2.1, 6.5 and 26 mTorr. Here, L was 15 cm. The model[7] employed here was as follows. Plasma occupied the spatial region of $0 \leq x \leq L$. A linearly polarized plane electromagnetic wave with an electric field E_y and a magnetic field B_z entered the plasma at $x = 0$, and a conducting boundary existed at $x = L$ with $E_y = 0$. We used the nonlocal conductivity of the bounded plasma,[3] the linearized Boltzmann equation with the Krook model collision operator and Maxwell's equations for deriving the electromagnetic fields in the plasma. Note that the component of the field was different between the experiment (B_z vs z) and the calculation (B_z vs x) due to the use of a one-dimensional model, but the underlying physics is the same between them because our interest here is whether or not there is a local relation between the dominant excited electric field and the current density in the plasma. The dominant current (experiment: θ component, calculation: y component) produces the z component of the magnetic field. Therefore, we specify x instead of z as the horizontal axis in the figure in the calculation. Comparing Figs. 1 and 2, good agreement between experiment and calculation was found. The point of minimum amplitude, which is related to the drastic change of the phase, shifted to a positive z-position with the lower P. The pressure dependence of the wave structure came from the change of the skin depth depending on the n_e and T_e values; the skin depth is greater with smaller n_e and higher T_e, including electron thermal motion at low filling pressure.

In order to check the collisionless (i.e., nonlocal) model, the conventional classical (i.e., local) model without electron

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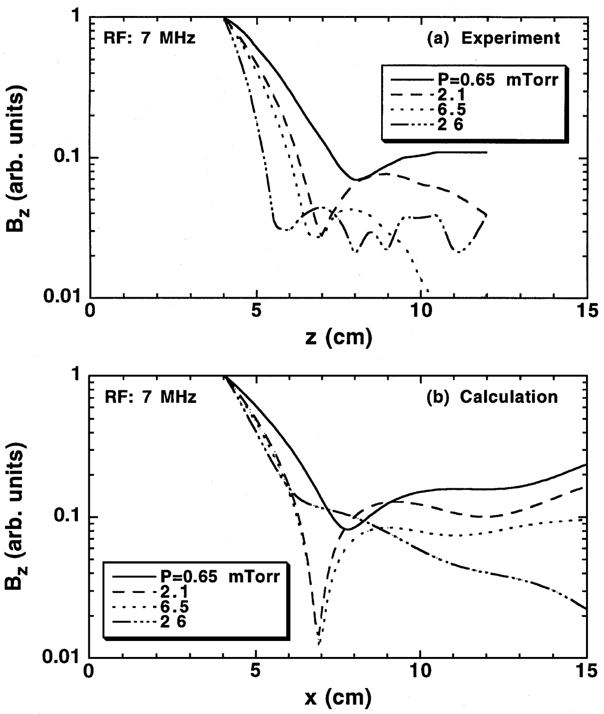

Fig. 1. (a) Axial profile of measured amplitude of the excited magnetic field B_z and (b) one-dimensional profile calculated using collisionless model, for the case of the boundary condition of $L = 15$ cm.

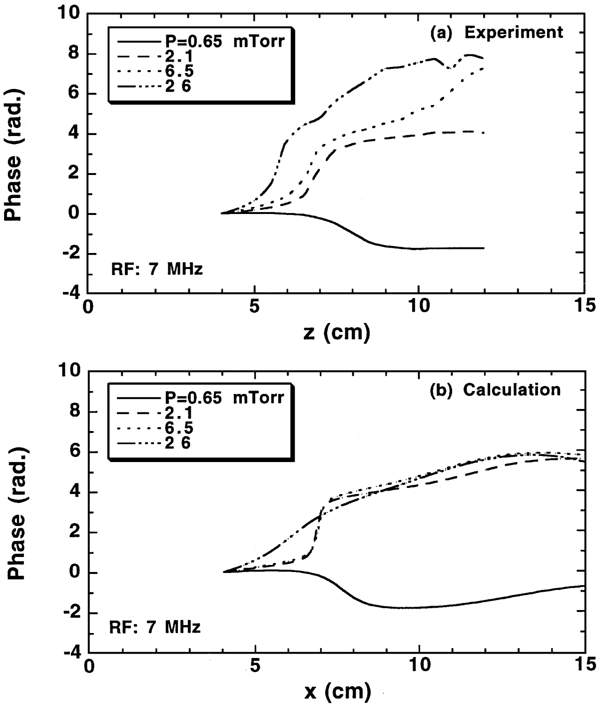

Fig. 2. (a) Axial profile of measured phase of B_z and (b) one-dimensional profile calculated using collisionless model with $L = 15$ cm.

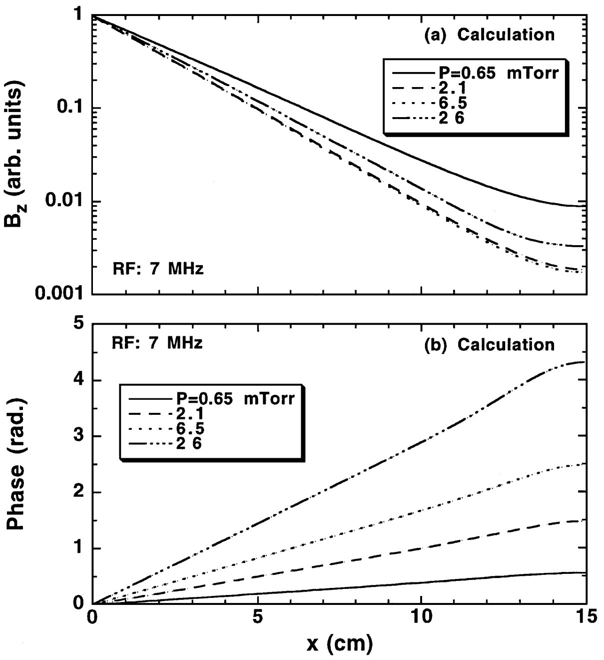

Fig. 3. One-dimensional profiles of (a) amplitude and (b) phase of the excited magnetic field B_z, calculated using collisional model with $L = 15$ cm.

thermal motion was examined. In the same bounded plasma as above, we used the local conductivity which is derived from the fluid equation, including the collision term, instead of from the Boltzmann equation. Figure 3 shows the calculated axial profiles of (a) amplitude and (b) phase using the classical model with the same plasma parameters as in Figs. 1 and 2. It was found that both the amplitude and the phase changed only monotonically, which did not agree with the experimental results. It is confirmed from the results shown in Figs. 1–3 that the observed behaviour of the evanescent wave could not be explained without including the effect of electron thermal motion (i.e., nonlocal model).

The boundary was changed from $L = 15$ cm to 30 cm and the observed axial profiles of the amplitude of B_z are shown in Figs. 4(a) (experiment) and 4(b) (calculation). The calculated result including the phase (not shown) could explain the experimental one well. It was also found that the pressure dependence is similar to that in Fig. 1, but the point of minimum amplitude was at a more positive z-position compared to the one in Fig. 1. This can be considered to be partly due to the weaker resonant coupling between the field and the electron bounce motion from the boundaries (and also partly due to the change of the plasma parameters). Considering the ratio of $2L/v_{\text{th}}$ (v_{th}: electron thermal velocity) to the RF period of $1/f$, which indicates the degree of resonance,[7] the resonance becomes clearer if this ratio is a small integer. This ratio became larger by a factor of $\sim$2 in the case of $L = 30$ cm (from 1.3 to 2.1 for $L = 15$ cm, from 2.7 to 4.3 for $L = 30$ cm with increasing P). When L was larger than 30 cm with $P = 2.1$ mTorr, the position of the point of minimum amplitude did not change at all ($z \sim 8$ cm). Here, the effect of particle motion in skin depth δ_{s}[7] can be neglected since the ratio of $2\delta_{\text{s}}/v_{\text{th}}$ to $1/f$ is smaller than 1.

When f was changed from 7 MHz to 3 MHz with $L = 15$ cm, this point was indistinct compared to the case of $f = 7$ MHz. Although there were changes of the plasma parameters, this can be mainly understood in terms of the above resonance; the ratio of $2L/v_{\text{th}}$ to $1/f$ was less than 1, i.e., it was beyond the range of the resonance conditions.

Finally, the antenna-plasma resistance R_{p} was examined by changing the boundary position L. Figure 5 shows the experimental R_{p} value as a function of L with $f = 7$ MHz,

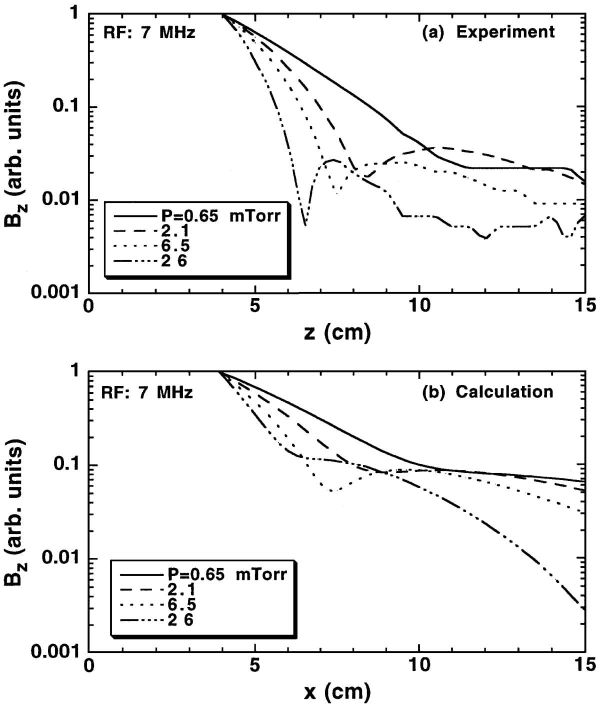

Fig. 4. (a) Axial profile of measured amplitude of B_z and (b) one-dimensional profile calculated using collisionless model with $L = 30$ cm.

changing the filling pressure P. It can be seen that the dependence of R_p on L became weaker as P became larger, and the peak value appeared more clearly with the small L value in the case of the low collisionality, i.e., low filling pressure. This peak may be a reflection of the stronger resonant coupling between the wave and electrons proposed in ref. 7. Note that experimentally, there was increased antenna-plasma resistance R_p with increasing electron density n_e in the ICP scheme. The effects of the resonance and n_e on R_p could not be distinguished in this work. However, the increased R_p with increasing n_e was clearer under low collisionality than high collisionality, which suggests the existence of the resonance phenomena under low collisionality, i.e., resonant coupling between the wave and the electron bounce motions became clearer.

In conclusion, we examined the effect of electron thermal motion in the ICP scheme using a spiral antenna. The measured amplitude and phase of the evanescent electromagnetic wave and antenna-plasma resistance, changing the boundary conditions, the filling pressure and the frequency, were compared with the results calculated using the one-dimensional model including electron thermal motion. This was the first attempt at the further verification of the role of electron motion under low collisionality. The point of minimum wave amplitude shifted on changing the boundary condition, the collisionality and the RF frequency, i.e., on varying the portion of the contribution of electron thermal motion. The observed peak antenna-plasma resistance under low collisionality suggested the existence of resonant coupling between the field and the electron bounce motion.

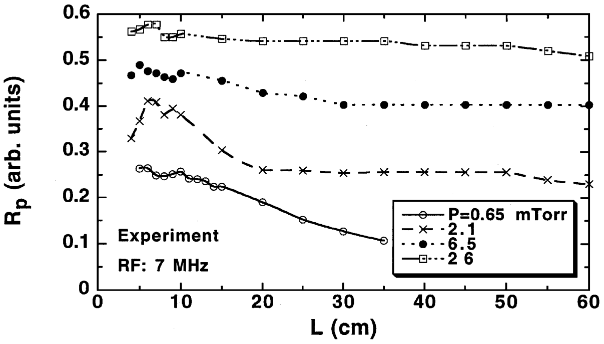

Fig. 5. Dependence of antenna-plasma loading resistance on L, changing filling pressure P.

Acknowledgement

We would like to thank Prof. Y. Kawai for his continuous encouragement.

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