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Experimental evidence for spatial damping of left-hand circularly polarized waves in an electron cyclotron resonance region

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Selective launch, propagation, and absorption of right-hand (R) and left-hand (L) circularly polarized waves are investigated using an inhomogeneously magnetized plasma. When the R wave gets closer to the electron cyclotron resonance (ECR) point, the wave vanishes in the strong magnetic-field region before reaching the ECR point. On the other hand, the L wave, which has been considered not to be related to ECR, is clearly observed to be also absorbed near the ECR point. The former and latter phenomena are discussed in terms of the contribution of high-energy tail electrons and polarization reversal of the L wave to the R wave within the plasma, respectively. © *2001 American Institute of Physics.* [DOI: 10.1063/1.1361256]

The electron cyclotron wave, or right-hand circularly polarized wave (R wave) is one of the fundamental plasma waves and its linear and nonlinear characteristics have been investigated so far.[1–3] Recently, much interest has been directed toward the application of the R wave to the plasma current drive,[4] suppression of major disruptions in tokamaks,[5] and formation of confining potentials in mirror devices,[6] because the R wave can realize the localized electron heating. As concerns this, it was reported that a spatially localized electron temperature elevation is observed near the electron cyclotron resonance (ECR) region and the R-wave absorption occurs at the same position as the temperature increase.[7] Furthermore, we have reported that ECR heating, or absorption of the R wave, plays an important role in the efficient electron heating and formation of plasma confinement potential in a simple mirror configuration.[8]

On the other hand, investigations on the propagation and absorption of high frequency (several GHz) microwaves in strong magnetic fields have been performed for the purpose of not only the efficient electron heating and the potential formation in fusion-oriented plasmas but also the high density and uniform plasma production for plasma processing. In a recent study, it was proposed to utilize the R wave as a means to produce very high density plasma because the R wave has no cut-off frequency, and the propagation characteristics of the wave were measured.[9] Furthermore, the influence of the wave propagating in a periphery of the ECR plasma on the plasma uniformity is investigated on the basis of possible mode conversion,[10] which was originally discussed in terms of polarization reversal between the R wave and left-hand circularly polarized wave (L wave) in an ECR discharge.[11,12] Since the microwave is simultaneously utilized for producing plasmas and studying wave behaviors, however, it is not easy to obtain clear-cut experimental results in these works and we are confronted by two unsettled questions. The first is that the wave absorption seems to occur far from the ECR point, and the second is whether the wave with a long wavelength like a L wave is also absorbed in the ECR region. Therefore, it is important to make experimental investigations on the propagation and absorption of not only the R wave but also the L wave, which are selectively excited in a steady-state high-density plasma. In this paper, measurements are performed on the wave propagation and absorption related to ECR in inhomogeneous magnetic fields.

Experiments are carried out in the Q_{T}-Upgrade machine, as shown in Fig. 1, which has a cylindrical vacuum chamber about 450 cm in length and 20.8 cm in diameter. A steady-state high-density plasma is generated by a direct current (dc) discharge between a 9.0 cm diam oxide cathode and a 10.0 cm diam tungsten mesh anode in a low pressure argon gas ($p \simeq 1\times10^{-4}$ Torr). A small Langmuir probe is used to measure electron density n_e and electron temperature T_e. Under our conditions, the electron density and temperature are $n_e = 1\times10^{10} \sim 2\times10^{11}\ \mathrm{cm}^{-3}$ and $T_e = 2-4$ eV, respectively. Typical magnetic-field configurations are also shown in Fig. 1. The magnetic-field B is changed so as to vary a characteristic length L_B of magnetic-field gradient, which is defined as $L_B = [(1/B)dB/dz]^{-1}$. A circularly polarized wave with frequency $\omega/2\pi = 6$ GHz and power $P_{\mathrm{in}} = 2.5$ W is launched into the plasma via a helical antenna located on the opposite side ($z = 0$ cm) of the plasma source ($z = 140$ cm). In these configurations, the wave propagates, satisfying the condition $\omega/\omega_{ce} < 1$, and attains the ECR point ($z = 78$ cm, $\omega/\omega_{ce} = 1$), where $\omega_{ce}/2\pi$ is the electron cyclotron frequency. The theory for this helical type of antenna is extensively developed in Ref. 13 and the antenna is designed to operate at the frequency $\omega/2\pi = 6$ GHz. This helical antenna can selectively launch the R wave or the L wave when the magnetic-field direction, or the electron Larmor-rotation direction, is changed. Here, we define the terms ''R-mode excitation'' and ''L-mode excitation'' as the excitation modes in the cases where the wave electric-field E rotates in the directions same as and opposite to the electron rotation, respectively. Spatial profiles of the wave power are measured using a movable dipole antenna with a power meter. In addition, the wave patterns are obtained with the interference method.

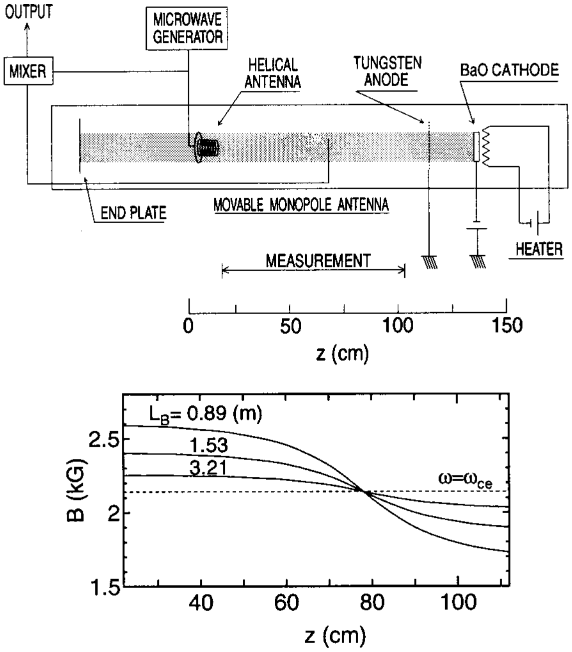

FIG. 1. Schematic of experimental apparatus and inhomogeneous magnetic-field configurations.

Figure 2 gives interferometric wave patterns at the radial center of the plasma column in the cases of (a) R-mode and (b) L-mode excitations in the inhomogeneous magnetic field with $L_B = 0.89\,\mathrm{m}$ for the discharge current $I_D = 10\,\mathrm{A}$. Here, solid arrows at $z = 78\,\mathrm{cm}$ indicate the position of ECR point. The wavelength of R-mode excitation is shorter than that of L-mode excitation. The measured dispersion relations in the cases of R-mode and L-mode excitations are in agreement with the theoretical dispersion relations of right-hand (R) and left-hand (L) circularly polarized waves in the boundary free plasma, respectively. This result demonstrates that the helical antenna described above can excite the R wave or the L wave by changing the magnetic-field direction. However, both the waves are slightly superimposed on each other, which is considered to be caused by an alignment deviation of the antenna or a mode conversion (polarization reversal) between the R and L waves as discussed later. Thus, the purely selective excitation of R wave or L wave appears not to be realized in the real situation.

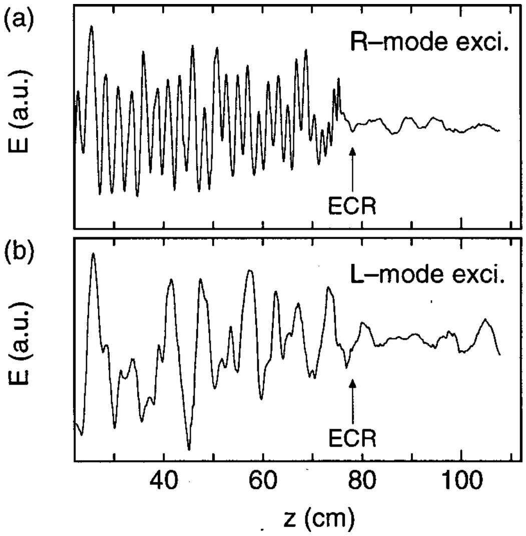

FIG. 2. Interferometric wave patterns at the radial center in the cases of (a) R-mode and (b) L-mode excitations in inhomogeneous magnetic field for $L_B = 0.89$ m.

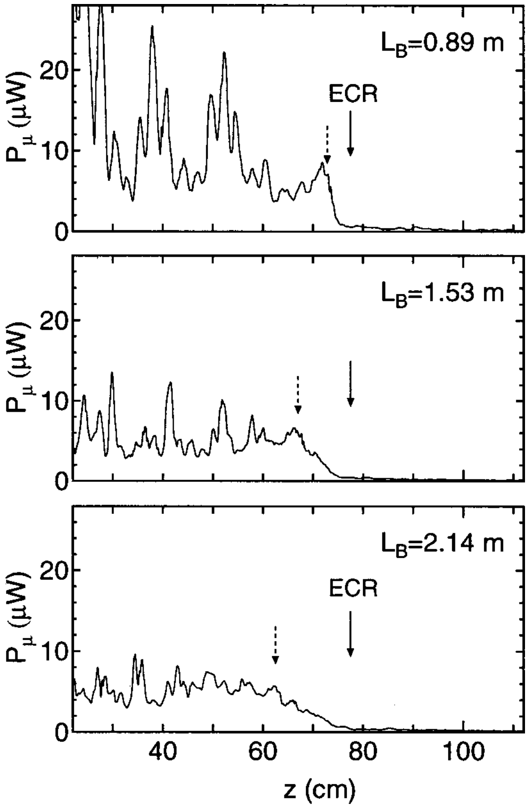

FIG. 3. Spatial profiles of received wave power P_μ in the case of R-mode excitation with L_B as a parameter.

The interferometric wave pattern in the case of R-mode excitation [Fig. 2(a)] demonstrates that the wavelength gradually becomes shorter and the amplitude steeply decreases as the wave reaches near the ECR point. The wave with short wavelength corresponding to the R wave vanishes in the strong magnetic-field region ($z \simeq 75\,\mathrm{cm}$) before reaching the ECR point, where the wavelength becomes too short to detect the signal of the R wave. In the weak magnetic-field side of the ECR point (plasma source region), however, a little amplitude of the wave still remains. This residual wave is considered to be the L wave which is slightly superimposed on the R wave or is generated by the polarization reversal from the R wave, because the R wave can never persists in this source region according to the theoretical dispersion relation. The interferometric wave pattern in the case of L-mode excitation [Fig. 2(b)], on the other hand, demonstrates that the wave with long wavelength which satisfies the L-wave dispersion relation propagates and is absorbed near the ECR point in the same way as the R wave. This result gives evidence for the absorption of the L wave in the ECR region, and its mechanism is discussed later.

Figure 3 presents spatial profiles of received wave power P_μ in the case of R-mode excitation for $I_D = 10\,\mathrm{A}$ with L_B as

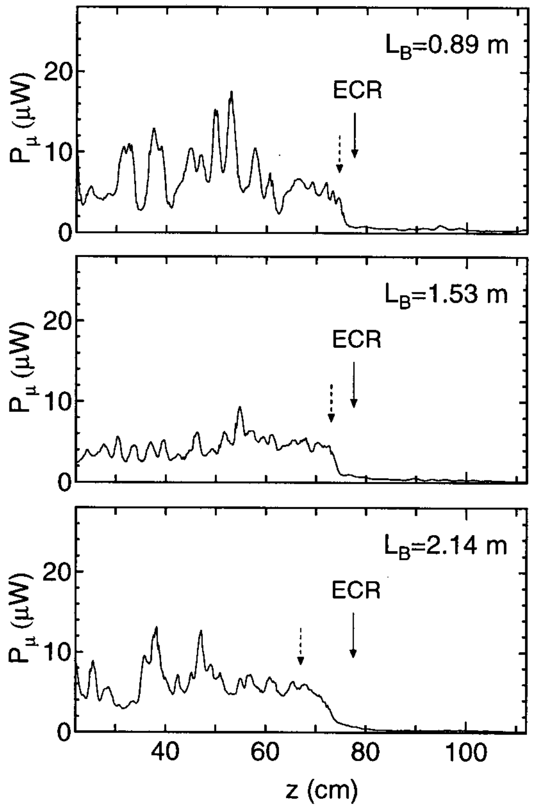

FIG. 4. Spatial profiles of received wave power P_μ in the case of L-mode excitation with L_B as a parameter.

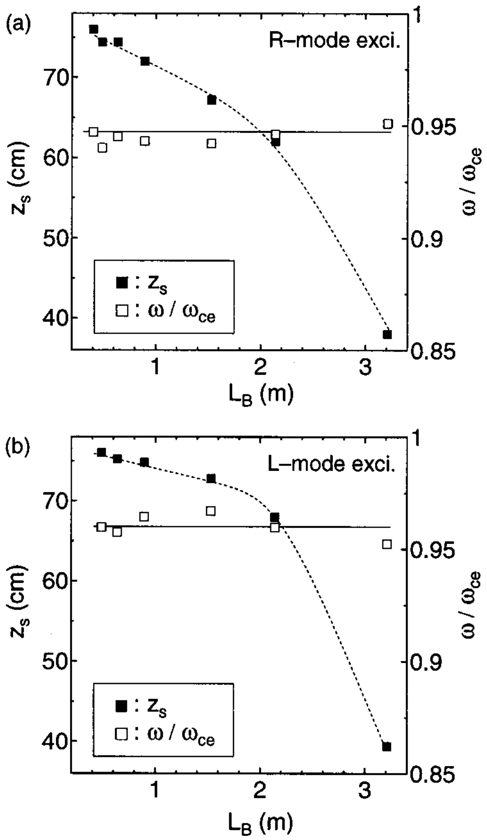

FIG. 5. Position z_s where the wave starts to damp and normalized frequency ω/ω_{ce} at this point ($z=z_s$) as a function of L_B in the cases of (a) R-mode and (b) L-mode excitations.

a parameter. When L_B is small, P_μ steeply decreases in the same way as the amplitude of the wave pattern as shown in Fig. 2, and the wave almost vanishes before reaching the ECR point. Here, the electron temperature is confirmed not to increase, because the absorbed wave power is very small (a few tens μW). As L_B increases, P_μ decreases in the whole region, and the position z_s at which P_μ apparently starts to damp (indicated by dotted arrows) moves to the antenna side.

Spatial profiles of received wave power P_μ in the case of L-mode excitation are presented with L_B as a parameter in Fig. 4. It is also clear that the wave almost vanishes around the ECR point and the starting position of wave damping z_s moves to the antenna side with an increase in L_B in the same way as the R-mode excitation. However, the residual wave power in the source region is larger and the shift of z_s is less than that of the R-mode excitation. It is to be noted that the evanescence of the L wave in the source region is not caused by the wave reflection at the ECR point, because the wave-power profile measured on the antenna side indicates a negligibly small contribution of the standing wave. On the other hand, measurements of the two-dimensional (radial-axial) wave-power profile indicate that the wave damps near the ECR point at any radial position within the plasma column. Thus, the evanescences of the L and R waves in the source region are confirmed not to be caused by a radial divergence of the wave-power flux near the ECR point.

Figure 5 shows the starting position of wave damping z_s (see Figs. 3 and 4) and the normalized frequency ω/ω_{ce} at $z=z_s$ as a function of L_B in the cases of (a) R-mode and (b) L-mode excitations. Here, the change of ω/ω_{ce} at $z=z_s$ means that of magnetic-field strength at the position because the input microwave frequency ω is kept constant under this experimental condition. In both the cases of R-mode and L-mode excitations, almost no change of ω/ω_{ce} (or the magnetic-field strength) at $z=z_s$ is recognized although z_s decreases with an increase in L_B, which indicates the wave absorption always starts depending on only the magnetic-field strength for fixed values of the other plasma parameters. These specific ω/ω_{ce} are 0.95 and 0.96 in the cases of R-mode and L-mode excitations, respectively. The R wave starts to damp at the position further from ECR point than the L wave. In order to clarify why the wave starts to damp at $\omega/\omega_{ce}=0.95$–0.96, the damping rate k_i/k_r is examined, where k_i and k_r are imaginary and real parts of the wave number, respectively. The experimentally obtained k_i/k_r around $z=z_s$ for $L_B=0.89\,\mathrm{m}$ is about 0.1–0.2, while k_i/k_r predicted by the linear theory for the boundary free plasma is less than 10^{-3} at $\omega/\omega_{ce}=0.95$–0.96 in the case of $n_e=2\times10^{11}\,\mathrm{cm}^{-3}$ and $T_e=3$ eV. Since the experimental damping rate is anomalously large compared with the theoretical one, we notice an electron distribution function measured around $z=z_s$. The electron energy distribution function is obtained from the first derivatives dI_p/dV_p, where I_p and V_p are the current flowing to and the voltage applied to the probe, respectively. Here, we observe a high-energy tail component of several percent of the bulk component, which is obtained from the value of the distribution function at such high energy. Assuming that these high-energy electrons of 20 eV, which is actually measured in this plasma, play a dominant role in the wave damping, the theoretical damping rates at $\omega/\omega_{ce}=0.95$ and 0.96 attains to $k_i/k_r=0.05$ and 0.15, respectively. Thus, the wave absorption in the high-field region is explained to some extent by the existence of the high-energy electrons in the plasma. The high-energy electrons have also a possibility to cause finite Larmor-radius effects on the absorption or a mode conversion to an electrostatic wave by the relativistic effect at the ECR point. However, these effects are considered to be negligible small, because the Larmor radius is much smaller than the plasma radius and the wave length, and the electron thermal velocity is much slower than the velocity of light even at $T_e=20\,\text{eV}$.

As described above, not only the R wave but also the L wave is absorbed and evanesces in the ECR region. When we take into account the boundary conditions at the plasma edge in the partially filled plasma waveguide, on the other hand, a mode conversion (polarization reversal) between the R and L waves can be expected to take place within the plasma.[11,12] Once the polarization reversal arises in the radial center of the plasma, the L wave is converted into the R wave at a certain rate, and vice versa. This is one of the reasons why each wave is superimposed on the other wave in Fig. 2. When these waves get closer to the ECR point, the R wave is immediately absorbed because of the strong increase in the damping rate, while the L wave is also absorbed as soon as it is converted into the R wave. Since this polarization reversal continuously occurs, the L wave appears to be absorbed in the ECR region in the same way as the R wave. The absorption efficiency of the L wave, however, is considered to be less than that of the R wave because the L wave is absorbed after the conversion into the R wave. As a result, the L wave starts to damp nearer the ECR point ($\omega/\omega_{ce}=0.96$) than the R wave ($\omega/\omega_{ce}=0.95$), as shown in Fig. 5.

Our experiment demonstrates that the right-hand (R) or the left-hand (L) circularly polarized wave can be selectively launched to some extent into a steady-state dc-discharge plasma with a helical antenna. When the R-wave is launched along the inhomogeneous magnetic-field lines, the interferometric wave pattern at the radial center shows that the R-wave wavelength gradually becomes shorter as the wave gets closer to the ECR point, and the wave vanishes before reaching the ECR point. The experimental damping rate at the position where the wave steeply begins to damp is anomalously stronger than that predicted by the linear theory for boundary free plasmas. This discrepancy is plausibly compensated by taking into account the effect of the high-energy tail electrons in the energy distribution. On the other hand, the wave with long wavelength, which satisfies the L-wave dispersion relation, propagates and is evidently absorbed near the ECR point in the same way as the R wave. This absorption of the L wave is considered to be caused by the the mode conversion (polarization reversal) between the R and L waves. Our results could be significant for the investigation of efficient ECR heating of plasmas.

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