Effects of cusp magnetic field configuration on wave propagation in large diameter r.f. produced plasma
Seiji Takechi *, Shunjiro Shinohara, Yoshinobu Kawai
Interdisciplinary Graduate School of Engineering Sciences, Kyushu University, Kasuga, Fukuoka 816-8580, Japan

Abstract

In order to investigate the effects of cusp magnetic field configuration on r.f. wave propagation, two-dimensional spatial profiles of the excited wave amplitude and phase were measured and were discussed with the spatial distributions of the ion saturation current in a large-diameter plasma. It was shown that in case of the cusp position near the antenna, the excited wave propagated obliquely to the chamber axis, whereas in the case of the position far from the antenna, beyond the position, the traveling wave disappeared. © 1999 Elsevier Science S.A. All rights reserved.

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1. Introduction

A helicon-wave-produced plasma [1–6] is regarded as one of the candidates for the high-density plasma source required for plasma processing and confinement devices. Various characteristics of the plasma, which is produced by radio frequency (r.f.) waves with the external magnetic field \( \omega c_\text{i} = \omega c_\text{e} \), where \( \omega c_\text{i} \) is the ion cyclotron angular frequency, \( \omega \) is the driving angular frequency, and \( \omega c_\text{e} \) is the electron cyclotron angular frequency, have been investigated in detail experimentally and theoretically. However, most of the results to elucidate the helicon wave physics were undertaken, for simplicity, with the uniform magnetic field. In the previous work, we demonstrated that a helicon wave with a dominant azimuthal mode number of \( m = 0 \) could be newly excited in a r.f.-produced plasma with a large diameter using a planar spiral antenna with the uniform magnetic field [7–9]. These results mean that this external magnetic field can be expected to be an additional control parameter for the plasma discharge. Therefore, by changing the various magnetic field configurations, we found that the effective diameter, \( D_{\text{eff}} \), defined as the region where the value of the ion saturation current is uniform within \( \pm 5\% \) reached \( \sim 27 \) cm in the cusp magnetic field configuration [10,11]. Therefore, an analysis of the wave characteristics in the cusp field configuration is very important for produced plasma profiles and also gives us an interesting wave physics, which has been scarcely studied. In this paper, we present experimentally observed spatial profiles of the excited wave amplitude and phase in a large-diameter r.f.-produced plasma with two cusp magnetic field configurations. The wave propagation characteristics and the comparison with the spatial profiles of the ion saturation current emphasizing the uniformity are also discussed.

2. Experimental

The experimental system was the same as that shown in fig. 1 of Ref. [7]. The four-turn spiral antenna (without Faraday shield) with a diameter of 18 cm was used. Here, \( z = 0 \) cm is defined as being at the window surface that faces an inner vacuum chamber \( \sim 45 \) cm in diameter and \( \sim 170 \) cm in length. The applied cusp magnetic field was generated by two coils: currents with the same magnitude have opposite directions each other. One case is that the line cusp position, \( z_{\text{cusp}} \), was 4 cm, and the central distance, \( d \), between the two coils was 36 cm (Case I). The other case is that \( z_{\text{cusp}} = 30 \) cm and \( d = 42 \) cm (Case II). A set containing a contour plot of the magnetic flux and a two-dimensional profile of the
magnitude of the magnetic field for both two cases are shown in Figs. 1 and 2, respectively.

The r.f. power supply was connected to the antenna through a directional coupler, a matching box and monitors of the antenna voltage and current. Here, the input power was ~300 W, with a frequency of 7 MHz and an Ar filling pressure of 8.5 mTorr in our experiments. The argon plasma parameters were measured by the use of movable and rotatable Langmuir and magnetic probes inserted axially (Case I: the typical measurement region was z=3~50 cm with r=0, 5, 10 and 15 cm; Case II: z=3~66 cm with r=0, 5, 10 and 15 cm, unless specified).

3. Results and discussion

Fig. 3 shows the axial profile of the ion saturation current, I_{is}, for Case I with (a) I_{c}=0 A (b) 30 A, (c) 60 A and (d) 100 A. As I_{c} increased, in the downstream region, I_{is} was uniform in the r direction. Previous work [10] showed that the effective diameter, D_{eff}, at z=30 cm reached ~27 cm at I_{c}=60 A, where the electron density n_{e}~2.5×10^{11} cm^{−3} and electron temperature T_{e}~2 eV (radial profile of I_{is} at z=30 cm became hollow at I_{c}=100 A, and the D_{eff} became shorter than that at I_{c}=60 A).

Figs. 1 and 2 show contour plots of the amplitude (phase) of B_{z} (axial component of the excited magnetic fields), in a logarithmic (linear) scale, for Case I with the coil current I_{c}=0, 30, 60 and 100 A. The intervals between the contour lines in Figs. 4 and 5 were 0.2 and π/2, respectively. In the case of no magnetic field, i.e. Figs. 4(a) and 5(a), the observing region was in a range of z=3~18 cm, and the amplitude damped strongly with the phase jump near the antenna region [see arrows in Figs. 4(a) and 5(a) at z~4 cm]. Needless to say, this wave was an evanescent wave in inductively coupled plasma [12], in contrast to a propagating wave, such as a helicon wave. As for the case of I_{c}=30 A [Figs. 4(b) and 5(b)], whose observing (detectable) region was in a range of z=3~21 cm, the penetration length of the wave was longer, and the z position of the phase jump increased (z=7 cm) as compared to those of the case of I_{c}=0 A, but this behavior for I_{c}=30 A was almost similar to that of the evanescent wave.

As for the case of (c) (I_{c}=60 A), the wave damped strongly near the cusp position, and then damped slowly over r–z space after passing through the cusp position. Beyond z=10 cm, the phase increased more slowly, i.e. the wave length became longer, but it deviated from the dispersion relation for a helicon wave with uniform plasma [2]. As for the case of (d) (I_{c}=100 A), beyond the cusp position, the amplitude had a tendency to peak.
Fig. 3. Axial profiles of ion saturation current $I_{is}$ for Case I with (a) $I_c=0$ A, (b) 30 A, (c) 60 A and (d) 100 A, respectively.

Fig. 4. Contour plot of amplitude in the excited magnetic field $B_z$ for Case I with (a) $I_c=0$ A, (b) 30 A, (c) 60 A and (d) 100 A.

Fig. 5. Contour plot of phase in the excited magnetic field $B_z$ for Case I with (a) $I_c=0$ A, (b) 30 A, (c) 60 A and (d) 100 A.
in the neighborhood of axis. The excited wave having longer wave length propagated further away from the antenna compared with the case of (c), and the wave length became shorter beyond the coil position \((z = 22 \text{ cm})\). These changes in wavelength, depending on the magnitude of the magnetic field, were consistent with the helicon wave characteristics expected from the helicon wave dispersion relation, but only qualitatively. Therefore, these results indicate that the excited wave propagated obliquely to the chamber axis direction because of the curvature of the magnetic field. Note that as for cases (c) and (d), the wave length at \(z < 10 \text{ cm}\) with \(r = 0\) and 5 cm, respectively, satisfied the helicon wave dispersion relation. In the case of (d), there was no traveling wave in the neighborhood of \(r = 15 \text{ cm}\).

In the case of \(I_c = 60 \text{ A}\), the best uniformity along the radial direction at \(z = 30 \text{ cm}\) was obtained, and the excited wave, beyond \(z = 10 \text{ cm}\), propagated obliquely to the \(z\) axis with damping slowly over \(r-z\) space. Comparison among these results suggested that it was necessary to obtain a plasma with good uniformity to consider the excited wave propagation region and/or angle with damping length.

Fig. 6 shows an axial profile of the ion saturation current, \(I_{is}\), for Case II with (a) \(I_c = 0 \text{ A}\), (b) 30 A, (c) 60 A and (d) 80 A. As \(I_c\) increased, the peak value of \(I_{is}\) shifted to a region further downstream. This result was similar to a previous study \([7]\) with an uniform magnetic field, in which a helicon wave with a \(m = 0\) mode was excited.

Figs. 7 and 8 show the contour plots of the amplitude (phase) of \(B_z\), in a logarithmic (linear) scale, for Case II with \(I_c = 0, 30, 60 \text{ and } 80 \text{ A}\). (in the case of \(I_c = 30 \text{ A}\), detectable region was in a range of \(z = 3 \sim 38 \text{ cm}\)). The intervals between contour lines in Figs. 7 and 8 were the same as in Figs. 4 and 5, respectively. Note that in the case of \(z_{cusp} = 36 \text{ cm} \text{ and } d = 100 \text{ cm}\), the observed radial profiles of the excited magnetic fields, at \(z = 30 \text{ cm}\), were identical to a helicon wave structure with a dominant azimuthal mode number of \(m = 0\). As for Case II, the excited wave length at \(z < 30 \text{ cm}\) satisfied the dispersion relation for a helicon wave. With a further increase in magnetic field with \(I_c = 30 \sim 80 \text{ A}\), the helicon wave was...
to be partly due to beat wave patterns between the fundamental and the higher-order radial modes [13, 14].

4. Conclusions

In order to investigate the effects of the cusp field on r.f. wave propagation, we measured two-dimensional spatial profiles of the excited wave amplitude and the phase with the ion saturation current distributions in the large-diameter (45 cm) r.f.-produced plasma under the two magnetic configurations. As for Case I, i.e. $z_{cusp} = 4$ cm and $d = 36$ cm, the ion saturation current $I_{is}$ was uniform in the $r$ direction, in the downstream region, with an increase in $I_{is}$. Only evanescent waves with $I_{is} < 30$ A were present, in contrast to a traveling wave with $I_{is} > 60$ A. When $I_{is} = 60$ A, at $z < 10$ cm, the wave first traveled in the $z$ direction initially within a limited region of $r < 5$ cm, and then propagated obliquely to the $z$ axis in a wide range of $r$-$z$ space. With a further increase in magnetic field ($I_{is} > 60$ A), the propagation region became narrow.

As for Case II, i.e. $z_{cusp} = 30$ cm and $d = 42$ cm, as the magnetic field increased, the effective plasma radius became larger, and the helicon wave was excited from any radial position of $r > 15$ cm from $I_{is} = 60$ to 80 A. Beyond the cusp position, the standing wave amplitude became larger. It was also shown that the unique behavior, probably due to beat wave patterns between the fundamental and the higher-order radial modes, appeared at $r = 5$ cm and $z = 10$ cm more clearly.

References