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Helicon $m = 0$ mode characteristics in large-diameter plasma produced by a planar spiral antenna

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Abstract. Excited wave characteristics in a large-diameter plasma produced by a planar spiral antenna are investigated. Radial and axial profiles of the excited magnetic fields, a dispersion relation and observing regions of the excited magnetic fields are studied, for variations in the filling pressure and the static axial magnetic field; successful excitation of the propagating helicon wave with an azimuthal mode number of $m = 0$ is shown.

1. Introduction

Plasma sources at high plasma density and low pressure are becoming more and more important for plasma applications and toroidal confinement devices. In order to meet, e.g., the industrial requirements, a helicon wave plasma [1–10] and inductively coupled plasma/transformer coupled plasma (ICP/TCP) [11] have been actively developed in the radio frequency (RF) range and some basic studies have also been conducted. In addition, a planar spiral coil [12–14] has been used in ICP, because of the advantage of the relatively simple geometry, but limited empirical characterization has been made.

Recently, a role of the Faraday shield, which is connected with reducing the unnecessary electric fields, and effects of the axial static magnetic fields on plasma performance were studied using the spiral antenna [14]. This trial showed the great importance of the electromagnetic fields in a large-diameter (45 cm) plasma, which is a critical issue for, e.g., the plasma processing field. In the presence of the static magnetic field, the excitation of the helicon wave was observed [14, 15]; this was the new excitation of the helicon wave and not the conventional one, since most of the experiments have been performed using helical, saddle or one-turn loop type antennae [10] wound around the (non-metal) discharge tube. However, the detailed helicon wave structures, including a dispersion relation, and experimental conditions to excite the helicon wave have not yet been investigated despite the development of this novel exciting scheme.

In this paper, we shall focus on the experimental studies of the detailed wave characteristics, excited by this planar spiral antenna, in the large-diameter plasma. Spatial excited wave structures and the dispersion relation are studied in section 3 in order to demonstrate the existence of the helicon wave, after a brief description of an experimental set-up in section 2. Furthermore, we present an investigation of the helicon wave exciting regions in the static magnetic field and filling pressure ranges in section 4, considering also the role of the Faraday shield. Finally, conclusions are presented in section 5.

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In [15], the shape of the vacuum chamber was not simple with a small axial length, and the divergent magnetic field was used, which led to some difficulties in analysing the wave phenomena (in addition, only one component of the radial magnetic field profile on the same axial position was reported). Note that, in our experiments, the simple geometry of the vacuum chamber (cylindrical shape, diameter 45 cm) with the long axial length (1.7 m), and the straight magnetic field configuration are used in order to facilitate the understanding of the basic wave nature.

2. Experimental set-up

Experiments have been carried out in the conventional linear device, as shown in figure 1, using the planar spiral antenna [14] with four turns and diameter 18 cm (the Faraday shield can be put on this antenna). A static axial magnetic field $B < 200$ G is applied, and the input RF power and frequency are ~1.7 kW and 7 MHz, respectively. The RF pulse width is 5 ms with a duty of 0.14. Plasma parameters using argon gas are measured by movable Langmuir probes inserted into the plasma radially and axially. Typical electron temperature and density are in the ranges 2–3 eV and 10^{12}–10^{13} cm^{-3}, respectively. The excited wave

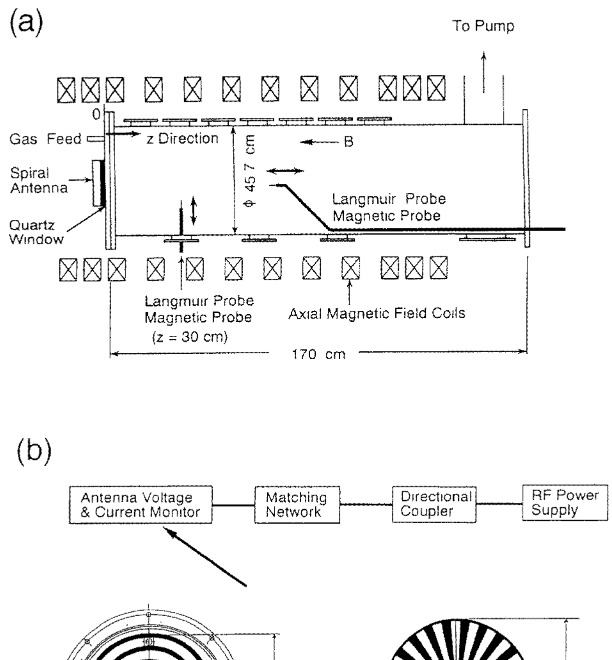

Figure 1. Schematic views of (*a*) the experimental apparatus and (*b*) the antenna structure including the RF system.

fields are measured by the movable magnetic probes (one-turn coil with ±2 mm spatial resolution) using the balanced mixer and the boxcar integrator.

3. Helicon wave characteristics

To check the wave propagation along the axial direction, as shown in figure 2, the excited magnetic fields are measured in the presence of the static magnetic field, for variations in the wave phase. For the interferometric wave measurements in this figure, both signals of the magnetic field by the probe, which is moving along the axial direction, and that of the antenna current for reference are put into the balanced mixer, and then into the boxcar integrator with a time window of 0.2 ms. Here, z is taken from the inner surface of the quartz window, facing the spiral antenna, to the direction towards the other end of the vacuum chamber. From this figure, we confirm that the wave propagates along the axial direction, i.e. from the antenna to the positive z direction through the inner vacuum chamber. The experimental damping length is $\sim$30 cm if we take the region $z = 20$–50 cm. This length is somewhat smaller than the estimated collisional damping length of several tens of centimetres and much smaller than the estimated electron Landau damping length of several metres in our experimental conditions, according to equations (79) and (108) of [2]. Here, the electron thermal velocity is comparable to the parallel phase velocity, while this phase velocity is smaller than that in the previous experiment with the smaller plasma radius of $\sim$3 cm, excited by the helical antenna [5, 7].

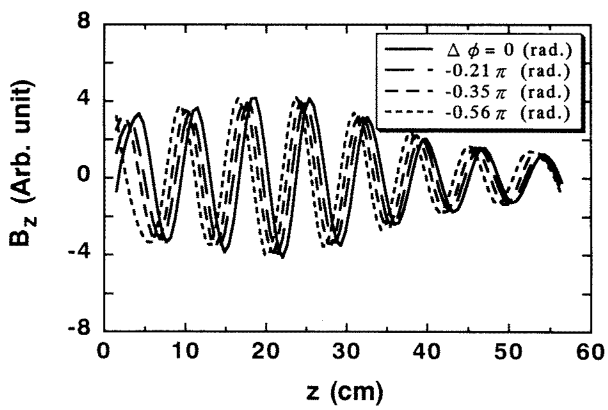

Figure 2. Axial profiles of the excited B_z field on axis measured by the interferometric method, for variations in the wave phase. Here, the filling pressure is $P = 26$ mTorr and the static axial magnetic field is $B = 72$ G with the Faraday shield.

Note that the ion saturation current I_{is} along the axial direction is nearly uniform (to be exact, I_{is} is smaller at $z \sim 0$ and 60 cm and becomes maximum at 20–30 cm) for this case of relatively low filling pressure [14]. This axial profile is different from that in the absence of the magnetic field (ICP case) [14]; this fact is considered to be partly due to the different plasma production region. This region along the z direction for the former case is broader because of the propagating wave, than the region (within an order of the skin-depth layer) for the latter case because of the evanescent wave. Needless to say, the plasma density tends to decrease towards the inner surface of the quartz window at $z = 0$ cm, which faces the antenna.

The reason why the B_z amplitude is slightly greater at $z = 20$–30 cm than nearer the antenna, as shown in figure 2, can be partly understood from the axial density profile and the dispersion relation of the helicon wave (low damping case). The excited wave amplitude A is derived by integrating the product [16] of the antenna spectrum by the inverse of the dispersion relation $D(k, \omega)$ over the wavenumber k (ω is the excited angular frequency). If $D(k, \omega)$ can be expanded with respect to the wavenumber at $k = k_0$, $D(k, \omega)$ is approximated as $D(k_0, \omega) + (k - k_0)\partial D(k_0, \omega)/\partial k$, where $D(k_0, \omega) = 0$. From the dispersion relation for the helicon wave [2], the wave amplitude A after the integration is nearly proportional to $k_0 = k_\|$, which scales approximately as the root of the plasma density n_e under our experimental conditions, i.e. $k_\|$ is greater than the perpendicular wavenumber $k_\perp$. From the estimation of the Poynting vector [6], the scaling of $A \propto n_e^{0.5}$ also holds good. This means that a larger wave amplitude can be expected for the higher plasma density case, keeping other parameters fixed as long as the excited antenna wavenumber spectrum is broad. Here, this spectrum is wider than the observed wavenumber by one order of magnitude. In fact, the density and wave amplitude at $z = 20$–30 cm are higher than those at $z < 5$ cm by about 50% and 20% respectively. This consideration can also be applied to the discussion of the damping length mentioned above; the experimental damping length looks shorter owing to the decaying electron density profile (along the z direction) at $z > 20$ cm.

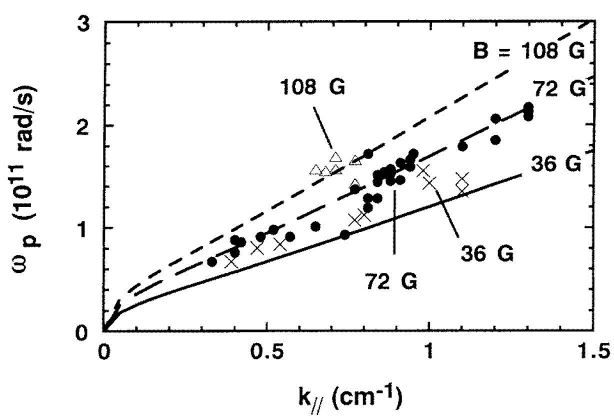

Figure 3. Relationship between plasma angular frequency ω_p and parallel wavenumber $k_\|$, for three cases of the static axial magnetic field $B = 36$, 72 and 108 G, with filling pressure $P = 4$–100 mTorr. Here, the calculated curves for each magnetic field case are shown for $m = 0$ helicon mode with flat density profile and plasma radius (effective excited wave region) $a = 8$ cm.

Figure 3 shows the relationship between the plasma angular frequency ω_p and the parallel wavenumber $k_\|$, for variations in the magnetic field B and the filling pressure P. Here, $k_\|$ is measured by the interferometric method (see figure 2) and ω_p is by the Langmuir probe (the electron density measurement, which is calibrated by the 70 GHz microwave interferometer). In this figure, theoretically calculated curves of the dispersion relation for the case of each magnetic field ($B = 36$, 72 and 108 G) are also shown for the helicon wave azimuthal mode number $m = 0$ [2] with a flat radial density profile and plasma radius (effective excited wave region) $a = 8$ cm. If $k_\|$ is much greater than the perpendicular wavenumber $k_\perp \sim 0.5$ cm^{-1} in the present case, $\omega_p/B^{0.5}$ is expected to be, roughly, proportional to $k_\|$. On the other hand, $k_\| k_\perp$ is proportional to ω_p^2/B from the dispersion relation, since $k_\perp$ is

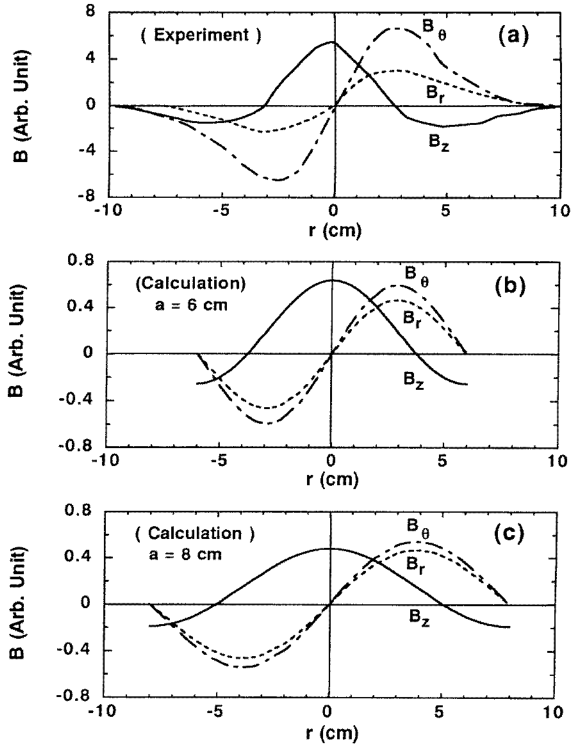

Figure 4. (*a*) Radial profiles of the excited magnetic fields (radial B_r, azimuthal B_θ and axial B_z components) measured by an interferometric method at $z = 30$ cm. Here, the static axial magnetic field is $B = 72$ G, the filling pressure is $P = 27$ mTorr in the absence of the Faraday shield. Calculated profiles of the three components of the excited magnetic fields for the $m = 0$ helicon mode are shown for plasma radius (effective excited wave region) $a = 6$ cm (*b*) and $a = 8$ cm (*c*) with uniform plasma density profile and parallel wavenumber $k_\parallel = 0.8$ cm^{-1}.

greater than $k_\parallel$ for the case of the smaller plasma radius (~3 cm) [5, 7].

Experimentally, the plasma density inside the wave excited radius of <10 cm (see figure 4) is nearly uniform, i.e. a drop of less than 10% in the central plasma density is found at the edge of this radius. Even if the density profile becomes parabolic, the ω_p value for the fixed value of $k_\parallel \sim 0.8$ cm^{-1} increases a little, by ~10% from the calculation. When the effective excited region of a increases (decreases) by 2 cm, the calculated ω_p value for $k_\parallel = 0.8$ cm^{-1} increases (decreases) by <5%. Taking this into account, figure 3 demonstrates that the excited wave well satisfies the dispersion relation for the helicon wave of $m = 0$ mode, and that there is no significant difference in this dispersion relation for the cases with and without Faraday shields.

Figure 4 shows the excited magnetic fields of three components (in the cylindrical geometry) using the interferometric method, in order to study the wave structures as a function of the radius. For comparison, calculated curves of the $m = 0$ helicon mode for two cases of plasma radius are also shown using the uniform plasma density profile [2]: $B_r = ck_\parallel J_1(k_\perp r)$, $B_\theta = c\alpha J_1(k_\perp r)$ and $B_z = ck_\perp J_0(k_\perp r)$, where c is constant, $\alpha = \sqrt{k_\parallel^2 + k_\perp^2}$, and J_0 and J_1 are Bessel functions. The experimental results in this figure show that the B_r and B_θ signals change sign (polarity) when crossing the plasma centre and the B_z signal becomes maximum at the plasma centre. This structure is completely different from those for the $m = 1$ and -1 modes [2, 4, 7] (B_r and B_θ signals becomes maximum and the B_z signal changes sign at the plasma centre), but it is similar to $m = 0$ mode. Here, the relative amplitude of the B_r (B_z) component is larger (smaller) than in the case with the smaller radius a ($m = 0$ mode) owing to the smaller $k_\perp$, which is consistent with the calculated results. Although the plasma is distributed in the whole region in the vacuum chamber of 45 cm in diameter, the excited wave region is limited to a diameter of $<$20 cm, which is nearly the same as the antenna diameter of 18 cm (this result is consistent with the expectation that the group velocity is nearly parallel to the axial direction, by virtue of the dispersion relation for the helicon wave [2]). If the plasma density profile becomes parabolic, which is not the case here, the calculated peak positions of B_r and B_θ decrease by $\sim$1.8 cm for $a = 8$ cm case, and the relative amplitudes of the two signals, B_r and B_θ normalized by that of B_z become lower by $\sim$33% and $\sim$45%, respectively. The numerical calculation also shows that increasing the parallel wavenumber $k_\parallel$ and/or the effective exciting radius a leads to an increase in the relative amplitudes of the B_r and B_θ signals, and an increase in the ratio of the B_r signal to the B_θ signal.

The experimental results and discussions mentioned above show that the excited wave satisfies the theoretical calculation of the dispersion relation and radial wave structures of the helicon wave; in addition to show that the excited standing (propagating) wave along the radial (axial) direction is observed: the excitation of the helicon wave of $m = 0$ mode within the region of 20 cm in diameter has been clearly identified for a large plasma diameter of 45 cm. Needless to say, taking into account the wave structures, a lower hybrid wave cannot be a candidate for the propagating wave under our experimental conditions.

4. Excited wave regions

The operating window for excitation of the helicon wave within the ranges for the static magnetic field B and the filling pressure P is studied (general plasma performance as a function of B and P, with and without the Faraday shields is reported in [14]). Figure 5 shows the relationship between the maximum amplitudes (in the radial direction) of three components of the excited magnetic fields and the static magnetic field B for both cases with and without Faraday shields, for the fixed filling pressure $P = 26$ mTorr. As B increases, the amplitudes of all three components increase, preserving the relation $B_\theta > B_z > B_r$, which shows no appreciable profile change of the excited fields in the radial direction. The amplitudes then saturate above around $B = 50$–100 G, which corresponds to a tendency for a gradual increase in I_{is} [14]. This may be related to the lack of the RF power density to sustain the higher plasma density. Above around $B = 150$–200 G, it is somewhat difficult to initiate the plasma.

As for the minimum B field for the excitation of the magnetic fields, we can observe the small amplitudes of the wave at $B = 18$ G for the case with the Faraday shield, while $B > 20$ G is necessary for excitation of the wave in the case without the Faraday shield (see figure 5). Here, the electron cyclotron frequency, f_{ce}, is 50 MHz for $B = 18$ G, which is greater than the excited frequency $f = 7$ MHz ($f = f_{ce}$ for $B = 2.5$ G) by a factor of $\sim$6. The ion cyclotron frequency, f_{ci}, at $B = 18$ G is 0.7 kHz for the argon plasma with a single charge state. Hence, the requisite frequency condition for the helicon wave excitation, i.e. $f_{ci} \ll f \ll f_{ce}$, is satisfied in our experiments for $20 < B < 200$ G.

In these experiments, the plasma density is nearly uniform along the axial direction for the lower pressure range ($<$ several tens of mTorr) with the Faraday shield, while without the Faraday shield the static magnetic field $B >\gtrsim 50$ G is necessary in addition to obtain

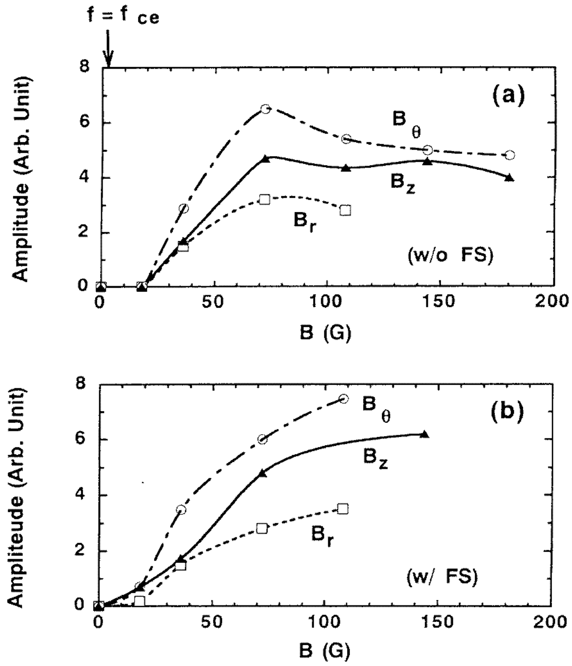

Figure 5. Dependence of the maximum amplitudes of excited magnetic fields (three components) at $z = 30$ cm and filling pressure $P = 26$ mTorr on the static axial magnetic field B for (a) with and (b) without the Faraday shields. The location at which the electron cyclotron frequency f_{ce} is equal to the excited frequency f is also shown for reference.

this nearly uniform profile. There is a difference in the Ar II line intensity behaviour [14] as a function of B in two cases, i.e. with and without the Faraday shields. These two observations reflect the result of figure 5 that the minimum B field for the helicon wave excitation without the Faraday shield is greater than that with the Faraday shield.

Figure 6 shows the relationship between the maximum amplitudes (in the radial direction) of the excited magnetic fields for three components and the filling pressure P for the fixed magnetic field B (=72 G). All three amplitudes change slightly, preserving the relation $B_\theta > B_z > B_r$ for P ranging from a few mTorr to a few tens of mTorr, and then decrease gradually until $P \sim 100$ mTorr. Above this transition point with P of a few tens of mTorr, the ion saturation current I_{is}, which is nearly constant along the axial direction (z) below this pressure point, decays with z, and also the value of I_{is} becomes smaller [14]. Here, there are no significant differences in behaviour in the cases with and without the Faraday shields.

5. Conclusions

Excited wave characteristics in the large-diameter plasma (diameter 45 cm) produced by the planar spiral antenna (RF frequency 7 MHz) are investigated. Radial (diameter of the excited wave region <20 cm) and axial excited wave characteristics, and the dispersion relation are studied, for variations in the static magnetic field. These results shows the successful excitation of the propagating helicon wave with azimuthal mode number $m = 0$. In addition, this wave can be excited for B in the range from a few tens of Gauss to

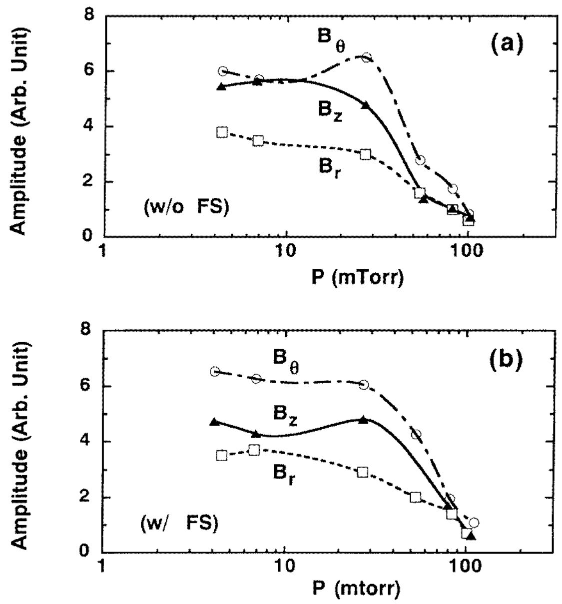

Figure 6. Dependence of the maximum amplitudes of excited magnetic fields (three components) at $z = 30$ cm and the static axial magnetic field $B = 72$ G on filling pressure P for (*a*) without and (*b*) with Faraday shields.

$\sim$200 G for $P = 26$ mTorr, and for P ranging from a few mTorr to a few tens of mTorr for $B = 72$ G, in our experimental conditions.

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