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Review Paper

Propagating Wave Characteristics for Plasma Production in Plasma Processing Field

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In this review paper, general wave characteristics and plasma production through excitation by propagating waves are outlined, with emphasis on plasma processing. First, the basic wave classification, characteristics and wave phenomena are summarized, with descriptions of resonance (damping), cutoff, polarization, wave energy and energy flux after introduction of a dispersion relation. Next, an analysis of various propagating waves and methods of plasma production and/or heating by these waves are presented followed by a summary of typical wave diagnostics. Finally, after a description of the characteristics of propagating waves and current research in the plasma processing field, i.e., with a focus on electron cyclotron, surface and helicon waves, experimental helicon wave studies are described for the introduction of typical propagating wave measurements.

KEYWORDS: plasma production, plasma processing, wave character, propagating wave, electron cyclotron wave, surface wave, helicon wave, diagnostics

1. Introduction

The scientific study of plasma can be categorized into basically three fields: plasma physics, plasma chemistry and plasma engineering. The industrial applications of plasma,[1,2] which cannot be understood without combined knowledge of those fields, are very important because of demands for many high-technology industrial processes. In the field of plasma processing, the following conditions are required: *e.g.*, 1) large radical density (low electron temperature and high electron density), 2) significant isotropic ion flux (low pressure and tunable wafer biasing), 3) cold bulk ions and neutrals (low bulk electric field), and 4) a large-diameter plasma with good uniformity.

Plasma physics can be expected to play an increasingly essential role in this field, and an understanding of the nature of waves as a means of plasma production is definitely needed in most cases. Historically, wave physics has undergone great progress with advances mainly in nuclear fusion studies, in which plasma production, heating, current drive and profile control have been elucidated. With this experience in expanding knowledge related to wave physics, we must choose appropriate waves by considering basic requirements as well as ease of production, stability and nonlinearity. Next, through simplification of the launching structure (the experimental setup), research and development should be carried out with an emphasis on industrial requirements such as cost, endurance and the progress of work.

In this review paper, we concentrate on general wave characteristics and plasma production through excitation by propagating waves, especially in the plasma processing field. First, basic propagating wave characteristics such as resonance or damping, cutoff, polarization, wave energy and energy flux are explained after the introduction of a dispersion relation. Next, an analysis of propagating waves and methods of plasma production and/or heating by these waves are described, followed by a summary of typical wave diagnostics. Finally, with consideration given to the field of plasma processing, wave characteristics and current research on electron cyclotron, surface and helicon waves are described, and typical examples from our experimental helicon wave studies are presented for the introduction of propagating wave measurements.

2. Characteristics of Propagating Waves

A great variety of excited waves exist in plasma, and waves can be categorized in many ways: 1) based on the presence or absence of an external magnetic field, 2) by propagation angle with respect to this magnetic field, 3) by electrostatic and electromagnetic characteristics, and 4) by normalized frequency and wavelength. Features of a wave are also determined by various boundary conditions.

Using the mks units of the international system (SI), a cold plasma dielectric tensor K can be represented by

$$\mathsf{K} = \begin{pmatrix} S & -\mathrm{i}D & 0 \\ \mathrm{i}D & S & 0 \\ 0 & 0 & P \end{pmatrix}, \tag{1}$$

where each element is defined in the usual way.[3,4] Using the relation $\boldsymbol{n} \times (\boldsymbol{n} \times \boldsymbol{E}) + \mathsf{K} \cdot \boldsymbol{E} = 0$ ($\boldsymbol{E}$: electric field) derived from Maxwell's equations with the refractive index $n = kc/\omega$ (ω: excited angular frequency, k: wave vector, c: velocity of light), the value of n^2 can be estimated from eq. (1).

For the case of cold plasma with a single ionic species and parallel or perpendicular propagation with respect to the static magnetic field, we have cutoffs $n = k = 0$, i.e., $\omega = \omega_{\mathrm{R}}$ from $S + D = 0$, ω_{L} from $S - D = 0$ and an electron plasma angular frequency ω_{pe} from $P = 0$ for four kinds of waves:[1,3,4] R, right-hand circularly polarized wave; L, left-hand circularly polarized wave; X, extraordinary wave, and O, ordinary wave. The resonances of $n = k = \infty$ in order of high to low frequencies are as follows: upper hybrid ($\omega = \omega_{\mathrm{UH}}$), electron cyclotron ($\omega_{\mathrm{ce}}$), lower hybrid ($\omega_{\mathrm{LH}}$) and ion cyclotron ($\omega_{\mathrm{ci}}$) resonances. In addition to the above resonances, electron and ion Landau damping, collisional damping, transit time damping and other damping processes (*e.g.*, stochastic and nonlinear processes such as nonlinear Landau damping and

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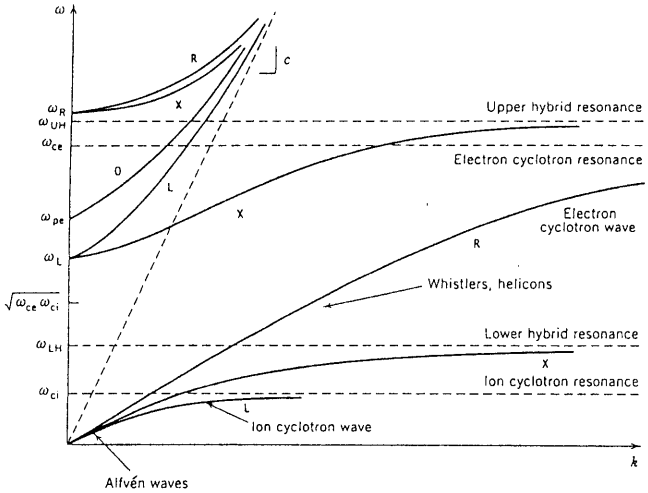

Fig. 1. Dispersion relation on (excited angular frequency ω, wave number k) plane for the principal waves in a magnetized plasma[1] Here, R and L (X and O) waves have parallel (perpendicular) wave number components.

parametric instabilities) must be included for the decay of the wave amplitude. If necessary, we must consider a kinetic effect using a hot plasma dispersion[3,4] instead of a cold one. The Clemmow-Mullay-Allis (CMA) diagram,[1,3,4] i.e., ω_{ce}/ω vs $(\omega_{pe}^2 + \omega_{pi}^2)/\omega^2$, which is equivalent to the relationship between the magnetic field and density, gives a comprehensible picture of electromagnetic waves in an unbounded cold plasma: cutoff, resonance, propagation boundaries and the dependence of phase velocity on the propagation angle for individual modes (ω_{pi}: ion plasma angular frequency).

Figure 1 (ref. 1) shows a dispersion relation on the (excited angular frequency ω, wave number k) plane for the principal waves from the cold plasma dispersion relation described above. Here, k has a parallel (perpendicular) component with respect to the magnetic field for R and L (X and O) waves. An electron cyclotron wave[1] (ECW; ω is slightly smaller than ω_{ce}) and a helicon wave[1] (HW: $\omega_{ci} \ll \omega \ll \omega_{ce}$), which are extensively used in plasma processing, lie on the same line and are categorized as whistler waves, as shown in Fig. 1. A surface wave (SW),[1] which is also a propagating wave and is utilized for plasma production, does not need a magnetic field. The characteristics of different methods of plasma production by these three propagating waves, which will be described later in detail, are compared in Table I. Here, typical ranges of operating conditions are listed.

Note that in capacitively coupled plasma (CCP)[1,2] and inductively coupled plasma (ICP),[1,2,5] the excited radio frequency waves do not propagate. Wave characteristics and the plasma production mechanism have not yet been clarified in a neutral line discharge (NLD).[6] For additional information, see the discussions in refs. 1, 7 and 8 on skin depth that characterizes the penetration distance of the electromagnetic fields for the case of a non-propagating, evanescent wave. Here, ICP and plasmas produced by ECW, HW, SW and NLD yield lower filling pressures and lower plasma potentials with higher

Table I. Comparison of three different plasma production methods involving use of propagating waves in the plasma processing area.

	Electron cyclotron wave	Helicon wave	Surface wave
f (MHz)	2450	5–30	1–10000
P (mTorr)	0.1–10	0.3–30	5–3000
B (G)	~875	50–1000	0
Antenna	waveguide, slot	coil	slot, waveguide surfatron, dielectric plate
n_e (cm^{-3})	10^{11}–10^{13}	10^{12}–10^{13}	10^{10}–10^{12}
Power absorption	electron cyclotron and collisional damping	collisional and electron Landau damping?	collisional and collisionless damping?

plasma densities than those in CCP, and RF bias voltages can be controlled independently from the individual plasma source, except for CCP.

In studies of nuclear fusion, in which various waves in high-temperature, high-density and fully ionized plasmas have been extensively investigated from the viewpoint of plasma heating, production and current drive, mainly the following waves are used depending on the objectives: 1) waves in the electron cyclotron frequency range (plasma production, electron heating and current drive by use of O and X waves with fundamental or harmonic electron cyclotron frequencies), 2) waves in the ion cyclotron range of frequency (ICRF) (ion and electron heating, current drive and plasma production with fundamental or harmonic ion cyclotron frequencies with use of the fast magnetosonic and ion Bernstein waves), 3) lower hybrid waves (current drive, plasma production, and ion and electron heating), and sometimes 4) Alfvén waves (electron and ion heating).

From Fig. 1, in addition to whistlers, we can see propagating waves such as a lower hybrid wave, an ion cyclotron wave and an Alfvén wave. Here, by use of the lower hybrid wave, high-density (n_e) plasma production at more than 10^{13} cm^{-3} was possible with a coaxial plasma gun at excitation frequencies f of 73 MHz and 2.45 GHz with an axial magnetic field B of less than 15 kG and an RF power P_{rf} of several kW.[9] An application of this wave to plasma processing has been initiated numerically and experimentally.[10] In the ICRF with rotation field excitation (Type III antenna excitation), dense plasma production at more than 10^{13} cm^{-3} was achieved in an open-ended machine, RFC-XX, where $f = 13.7$ MHz with a high field of $B > 10$ kG and a high power of $P_{rf} > 100$ kW.[11] In any case, wave power is transferred from an oscillator, generally through coaxial cables or waveguides, depending on the excitation frequency and the experimental conditions, to the different antennae such as coils, horns and slots.

In summary, wave phenomena can be classified into three processes: wave excitation, propagation and damping. Sometimes, mode conversion,[3,4,12] mode transformation[13] and wave decay[4] occur. For understanding wave damping, estimation of wave energy W, energy flux

$\boldsymbol{S}$ and absorption power $P_{\rm abs}$ is important and is written as[3,4,14)]

$$W = \frac{1}{2}\mathrm{Re}\left[\frac{\boldsymbol{B}^*\cdot\boldsymbol{B}}{2\mu_0} + \frac{\varepsilon_0}{2}\boldsymbol{E}^*\cdot\frac{\partial}{\partial\omega}(\omega\mathsf{K}_{\rm h})\cdot\boldsymbol{E}\right]$$
$$= \frac{1}{2}\mathrm{Re}\left[\frac{\varepsilon_0}{2}\boldsymbol{E}^*\cdot\frac{\partial}{\omega\partial\omega}(\omega^2\mathsf{K}_{\rm h})\cdot\boldsymbol{E}\right], \qquad (2)$$

$$\boldsymbol{S} = \boldsymbol{P} + \boldsymbol{T},$$
$$\boldsymbol{P} = \frac{1}{2\mu_0}\mathrm{Re}(\boldsymbol{E}^*\times\boldsymbol{B}),$$
$$\boldsymbol{T} = -\frac{\omega\varepsilon_0}{4}\boldsymbol{E}^*\cdot\frac{\partial}{\partial\boldsymbol{k}}\mathsf{K}_{\rm h}\cdot\boldsymbol{E}, \qquad (3)$$

$$P_{\rm abs} = \frac{\omega\varepsilon_0}{2}\mathrm{Re}(\boldsymbol{E}^*\cdot\boldsymbol{K}_{\rm i}\cdot\boldsymbol{E}) = \frac{1}{2}\mathrm{Re}(\boldsymbol{E}^*\cdot\boldsymbol{j}). \qquad (4)$$

Here, μ_0, $\boldsymbol{j}$, the asterisk and Re are permeability in the vacuum, current density, a complex conjugate and real part, respectively. The term $\mathsf{K}_{\rm h}$ ($\mathsf{K}_{\rm i}$) is the Hermitian (anti-Hermitian) part of the dielectric tensor K. The Poynting vector and non-electromagnetic energy flux due to the coherent particle motions are expressed as $\boldsymbol{P}$ and $\boldsymbol{T}$, respectively.

In the calculation of wave structures, an analysis of electromagnetic fields imposed by the boundary conditions has been employed, *e.g.*, the electron cyclotron frequency range[15)] under realistic conditions in plasma processing, and a fast magnetosonic wave in the ICRF,[16)] with the differential equation from the cold plasma dispersion relation. If the wavelength in the plasma is much less than the scale length of the gradient, we can utilize a ray tracing scheme[3,4)] with the WKB method, *e.g.*, ECW, which shows refraction of the wave power toward the lower density region in cylindrical geometry,[17)] and the ion Bernstein wave.[18)] In addition, transport in plasmas[1,19)] must also be taken into account for understanding of the power deposition in a self-consistent manner.[15)]

Next, we consider briefly the diagnostic approach[20)] for the investigation of the nature of propagating waves. The amplitude and phase of the magnetic fields of an excited wave as functions of space can be measured using a magnetic probe,[20)] which also gives information on the wavelength as well as the polarization. A Langmuir (electric) probe can also be used for wave measurements of the excited electric fields, but one must distinguish the electromagnetic component from the electrostatic one in the signal.[21)] Sometimes interferometric wave measurement for the determination of the amplitude and wavelength is employed with a balanced mixer and attenuators, and a phase shifter is also useful for checking the wave propagation. Relative plasma density, which is used, *e.g.*, to obtain the dispersion relation, can be measured by an electric probe.[20)] The absolute density is determined by use of a microwave or laser light interferometer;[20)] this system can also be used to measure the slowly varying magnetic field profile inside a plasma.[20,22,23)] Absolute density can also be measured by a microwave cavity resonance method in the absence of a static magnetic field.[24)] Generally, in the measurements we must account for gain, frequency response, spatial resolution and noise reduction. For averaging the data obtained, a boxcar integrator can be utilized for the case of a pulsed wave, and a spectrum analyzer and a lock-in amplifier are also useful.

If the wave has an electrostatic nature which causes electron density fluctuations, a scattering method with laser light or microwave beams[12,20)] is used to determine the wave number. General laser diagnostics for the measurements of, for example, electron temperature, density, electric field and magnetic field in high-temperature or processing plasmas are reviewed in ref. 25. On the other hand, if the dispersion relation is determined, we can estimate the plasma parameters, such as ion temperature from the ion Bernstein wave.[13)] Here, ion temperature is usually measured by the methods of Doppler broadening of spectral lines,[20)] time-of-flight analysis,[20)] gridded energy analyzer,[20)] charge exchange neutral particle analyzer,[20)] or use of an ion-sensitive probe.[26)] In addition, if radial structures of the helicon wave electromagnetic fields are measured for the case of excitation of a single radial mode, an electron density profile can be estimated.[27)] Therefore, propagating waves are also important for plasma diagnostics if the nature of the wave is well known.

Optical emission spectroscopy (OES) is useful for determination of the plasma generation region; plasma light provides information on spectral lines of various ionization states and on the electron density and temperature.[20,28)] For the estimation of the electric field profile of the wave, a microwave electric field probe was used to measure the energy absorption in the ECW-produced plasma,[29)] and the two-dimensional electric field distribution was inferred from the change in the color of thermally sensitive paper located outside the plasma excited by ECW.[30)] In most cases in plasma processing, the ratio of the radiated power, which may be measured by a bolometer,[20)] to the total power loss is considered to be negligible compared to the tokamak results.[31)]

3. Electron Cyclotron and Surface Waves

An application of electron cyclotron resonance to plasma production[1,32)] has been attracting much attention in the nuclear fusion field as well as the plasma processing one. However, contrary to the use of O and X waves in nuclear fusion, an ECW has been utilized most in plasma processing due to the high wave absorption rate even in low-density and low-temperature plasmas and due to the good wave accessibility condition. It is known that the dispersion relation for high-frequency electromagnetic modes is given by the Appleton-Hartree relation.[3)] Under some approximations of this relation, the R (ECW) wave (upper sign) and the L wave (lower sign) in the electron cyclotron frequency range are given by the following expression:[3)]

$$n^2 = 1 - \frac{\omega_{\rm pe}^2}{\omega(\omega \mp \omega_{\rm ce}\cos\theta)}. \qquad (5)$$

Here, θ is the propagation angle with respect to the static magnetic field.

In electron cyclotron discharges for plasma production, an excited ECW is absorbed near the electron cyclotron resonance (ECR) angular frequency at $\omega \sim \omega_{\rm ce}$ (to be exact, at the Doppler-shifted electron cyclotron angular frequency), and this wave amplitude also decays due to the collisional damping process. This damping effect can be incorporated in the dispersion relation by replacement of electron mass m_e by $(1+i\nu/\omega)m_e$,[1,3,8,15,33] where ν is the electron collision frequency. For the case of hot plasma, the second term on the right-hand side of eq. (5) must be replaced by the plasma dispersion function term,[3] but an appropriate choice of ν_e, the equivalent collision frequency, can allow accurate absorption calculation for cyclotron damping under certain conditions.[15] This cyclotron damping was experimentally studied,[34] and generally the excited wave from the higher magnetic field side is almost entirely absorbed before the ECR zone, where $\omega/\omega_{ce} < 1$. Figure 2 shows an example of the ECR experimental system. A static magnetic field B above 875 G is necessary for R wave propagation when f = 2.45 GHz, and usually a divergent magnetic field configuration is used. Note that the L wave can propagate through the ECR layer without being absorbed. The plasma density n_e is generally in the 10^{11}–10^{13} cm^{-3} range, although values above 10^{13} cm^{-3} are possible,[35] with a low filling pressure on the order of mTorr (see Table I).

There are many means by which to achieve large-diameter plasma production with good uniformity,[35–40] *e.g.*, multislots, multipole magnetic fields and a cavity, and sometimes the distance between the antenna and the resonance zone is short enough for the wave to propagate. The plasma profile obtained is sensitive to many factors[17,29,35,41,42] such as the magnetic field configuration, the mode of the waveguide, the wave power and the filling pressure. Recently, pulse-time modulation of wave power[43] was applied to change the plasma parameters for processing requirements. For the analysis of wave propagation and produced plasma parameters, several attempts[15,17,44–47] have been made to simulate the time evolution of the behaviors of the experimental plasma, which must be understood in a self-consistent manner by inclusion of plasma transport.

Next, a SW,[1,48–51] which was first observed under a dc discharge, is briefly described. Even without external magnetic fields, this wave propagates along a cylindrical column, having strong excited fields only near the plasma surface with an azimuthal mode number m, and is efficiently absorbed by the plasma. Due to advances in this field, a wide range of operational windows such as the excitation frequency and the filling pressure is now possible (see Table I; the pressure domain sometimes extends from 10^{-5} Torr range to about 3 times the atmospheric pressure). Examples of the dispersion relation of this wave in the planar and cylindrical cases are described in ref. 1. Generally, the exact solution is a combination of transverse magnetic (TM) and transverse electric (TE) waves, and the SW has an electromagnetic (electrostatic) character for the low (high) wave number region.

First, a cylindrical plasma up to about four m long[52,53] with a small diameter was produced by application of strong RF electric fields at the launcher (see Fig. 3(a)), and the dispersion relation of this wave was confirmed.[55] Launchers such as the Ro-box field applicator and (waveguide) surfatron were utilized, depend-

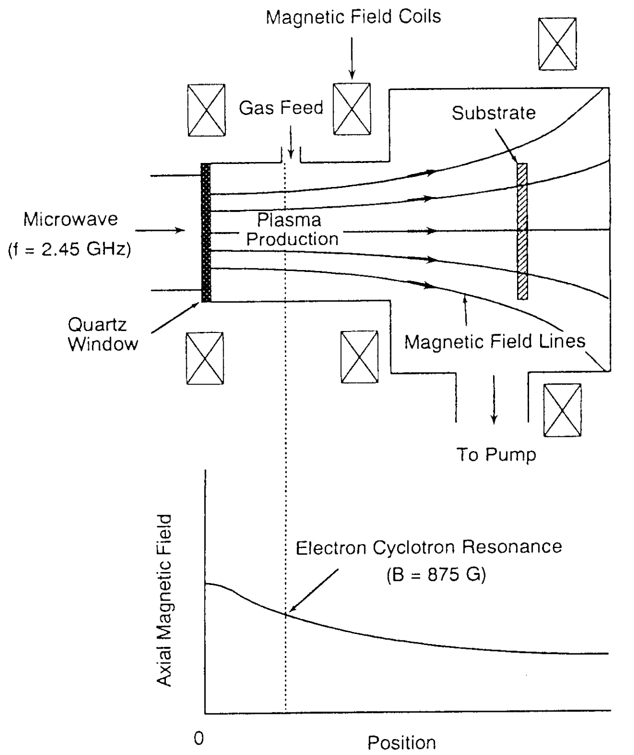

Fig. 2. Example of ECR system, showing geometric configuration and axial magnetic field variation.

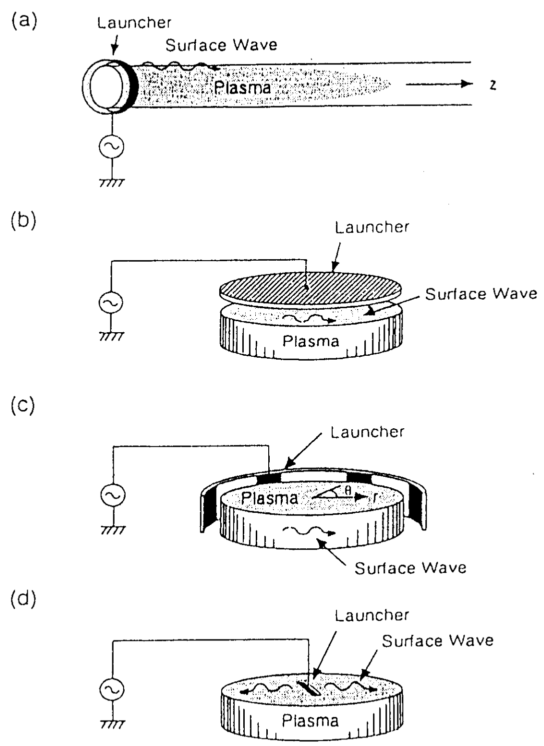

Fig. 3. Conceptual drawings of various types of microwave launchers for production of surface wave plasmas.[54]

ing on the exciting frequency, and to meet the requirements of larger-diameter plasma production in processing, improved launchers were developed.[56,57] In addition, a large planar launcher with a dielectric plate,[58–61] as shown in Fig. 3(b), a slot antenna[62] at the side surface,[63,64] as shown in Fig. 3(c), and a slot antenna at the top surface,[65–67] as shown in Fig. 3(d), have been tried. More recently, a coaxial antenna was developed.[68] However, except for surfatron-type excitation, the role of the SW for plasma production has not yet been fully verified.

As for theories about this wave, electric fields and plasma density in the cylindrical geometry were estimated[69–71] for a case of weak damping with $\nu < \omega$. Here, α and θ, which are the decay constant of the energy flux along the axial direction and the mean energy loss per unit time, unit length and one electron, respectively, are introduced for the analysis. In addition, analyses including consideration of a nonlinear effect[72] or for the case of planar plasma[73] were recently attempted, but generally, many problems still remain to be solved.

In summary, although the SW has been studied for a long time, further investigation is necessary. The nature of this wave, *e.g.*, its damping mechanism (energy transfer from the surface wave to electrons) and self-consistent analysis of the wave and its discharges, is not fully understood, and the excitation methods for producing a large-diameter plasma, including stabilization of the discharge mode and axisymmetry, have not been extensively developed. In addition, the typical operating pressure range (see Table I), which is generally higher than the electron cyclotron wave and helicon wave discharges, must be lowered in the real device for large-diameter plasma processing.

4. Helicon Wave and Typical Examples of Wave Studies

After finding a helicon wave (HW)[1,74] as a low-frequency whistler ($\omega_{ci} \ll \omega \ll \omega_{ce}$),[75] Boswell discovered it to be a plasma production source with a high density of up to more than 10^{13} cm^{-3} and with a high ionization rate.[76,77] Many researchers have studied the characteristics of this wave and its plasma performance[33,78–88] and are utilizing it extensively as a means of semiconductor etching and deposition.[80,89–92] In addition, this wave can be used for ArII laser generation[93] and plasma production in a heliac fusion device.[94] The dispersion relation of this bounded whistler wave for the case of a uniform radial density profile[95] is written as

$$[k_{/\!/}^2 + k_\perp^2]^{0.5} = \frac{\omega}{k_{/\!/}} \frac{\omega_{pe}^2}{\omega_{ce} c^2}. \tag{6}$$

Here, $k_{/\!/}$ and $k_\perp$ are parallel and perpendicular wave numbers, respectively. The term $k_\perp$ is determined by the boundary conditions. Figure 4 shows an example of this relation with the azimuthal mode number $m = 0$. The electromagnetic fields are expressed as a combination of Bessel functions, and the typical electric field line patterns with $m = 0$ and $m = 1$ modes are shown in ref. 95. The dispersion relation for the case of an arbitrary density profile is discussed in ref. 27.

This plasma, whose high density is established after a drastic density jump (sometimes three phases of capacitive, inductive and HW modes are detected[88]), can be produced using several types of antennae, as shown in Fig. 5: a loop antenna (one or more turns, or double half-turns), an antenna with no helical pitch angle (sometimes called a type III antenna), an antenna with

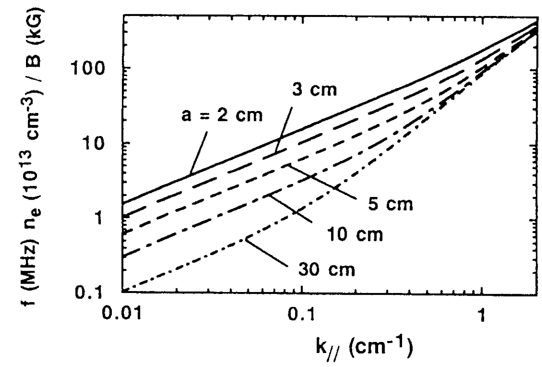

Fig. 4. Dispersion relation of helicon wave with azimuthal mode number $m = 0$ with uniform radial density profile (a: plasma radius). Here, excitation frequency f, electron density n_e, axial magnetic field B and parallel wave number $k_{/\!/}$ are in units of MHz, 10^{13} cm^{-3}, kG and cm^{-1}, respectively.

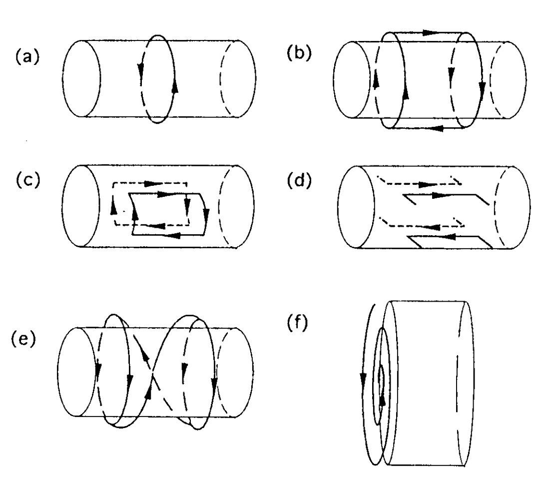

Fig. 5. Various types of antennae for excitation of a helicon wave: (a) loop antenna, (b) antenna with no helical pitch angle, (c) antenna with double saddle coils, (d) type III antenna, (e) helical antenna with half-wavelength and (f) spiral antenna.

double saddle coils, a type III antenna (for which the azimuthal mode number can be excited by selection of the appropriate choice of current phase between the four rods), a helical antenna with half wavelength and a spiral antenna. A helical antenna with full wavelength was also tried and separate excitation of $m = 1$ and $m = -1$ modes was possible by changing of the direction of the static magnetic field. These antennae except for the spiral antenna are wound around a nonmetal tube with a source diameter of mostly less than 20 cm, and a RF power of less than about 3 kW and a frequency of between 5 to 30 of MHz. The axial magnetic field is from 50 G to 1 kG typically, and at a low magnetic field where electron inertia cannot be neglected, a Trivelpiece-Gould (TG) mode with a short wavelength appears.[74] The typical working gas pressure is 0.3–30 mTorr (see Table I).

After examination of the excited wave using the dispersion relation, radial structures and polarization, it was found that the HW is excited in the plasma after the density jump (see, *e.g.*, refs. 81 and 84 and Figs. 7–9 described later), and simultaneous excitation of two radial eigenmodes is indicated in some cases.[83] However,

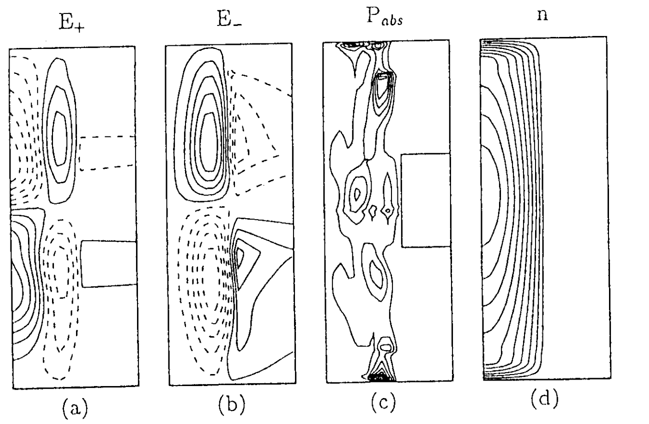

Fig. 6. Contour plots of (a) right-circularly polarized electric field E_+, (b) left-circularly polarized electric field E_-, (c) absorption power P_{abs} and (d) density n for $m = 1$ mode.[33]

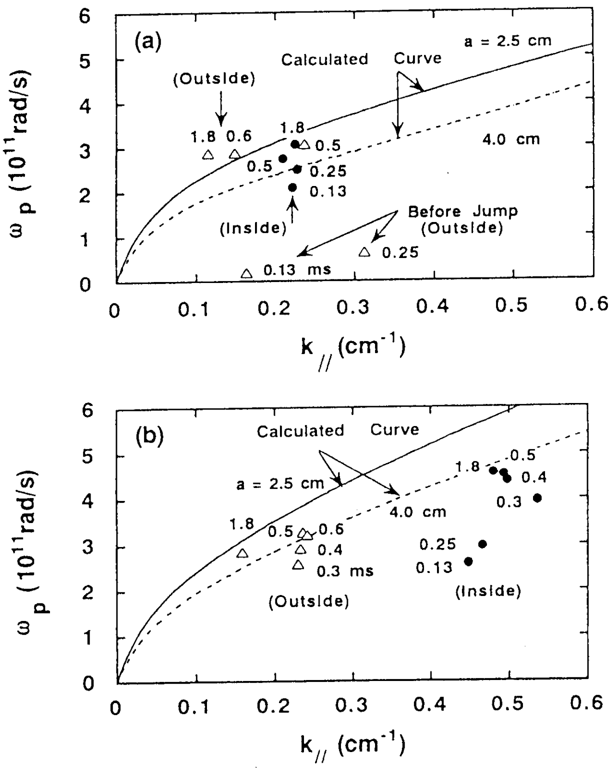

Fig. 7. History of the dispersion relation on (plasma angular frequency ω_p, parallel wave number $k_{/\!/}$) plane for (a) $m = 1$ and (b) $m = -1$ excitation.[81] Here, full circles and open triangles show cases measured inside and outside the antenna regions, respectively.

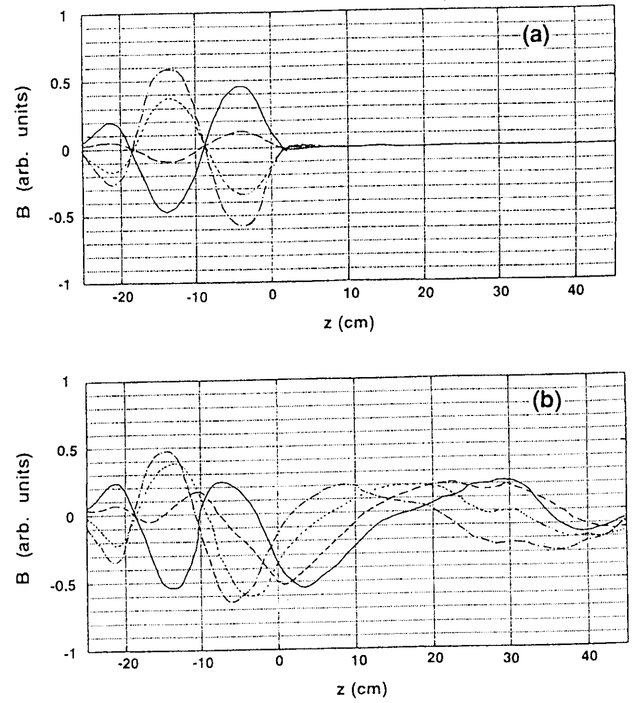

Fig. 8. Typical wave patterns of excited perpendicular magnetic field measured by the interferometric method at (a) $t = 0.03$ ms and (b) $t = 1.8$ ms for $m = 1$ excitation.[81] Here, full, broken, dotted and chain lines represent cases of phase $\Delta\phi = 0, -0.21\pi, -0.45\pi$ and -0.66π, respectively.

there is still a discrepancy concerning the separate excitation of azimuthal mode number: *e.g.*, the $m = 1$ mode is preferentially excited regardless of the antenna configuration,[82,85] or $m = 1$ and $m = -1$ can be excited separately.[33,79,81,84] Here, the plus (minus) sign of m denotes right-handed (left-handed) rotation with respect to the axial magnetic field. This discrepancy may be partly due to the different ionization rate, filling pressure or plasma density, and the antenna wave number spectrum. As for the antenna-plasma coupling, antenna loading increases drastically after the density jump.[79,81] However, the plasma production mechanisms are still open questions to be answered; electron Landau damping[78,87,95,96] which depends on the electron velocity distribution and especially on the existence of fast electrons, collisional damping[78,95] which may become important in the higher plasma density region, beam-plasma instability[74] and the antenna near field, or combined effects of these mechanisms, can be considered to be candidates. In this case, optical measurements on, *e.g.*, the ArII line emission in an Ar discharge, are also important to detect fast electrons.[97,98]

Here, we briefly mention the theoretical work, which is still not sufficient to explain the HW. Wave coupling was numerically investigated, and the findings can be understood reasonably well based on the antenna wave number spectrum and the dispersion relation.[99] The $m = 1$ mode is the most strongly excited one for commonly used antennae.[100] The TG mode is important for surface electron heating, and linear dependence of plasma density on the magnetic field was found.[101] The concept of resonance wave discharge was introduced to account for the high wave absorption efficiency.[102] The discharge equilibrium was calculated for the particle, pressure and energy balance,[103] and the radial transport by the $m = 1$ and $m = -1$ modes was discussed.[104] A two-dimensional simulation including transport was performed and the simulation results corresponded to the experimental ones.[33] Figure 6 shows an example of the calculated profiles of the electric field, power absorption and density.

In future studies, we must solve the many problems mentioned above experimentally and theoretically, and

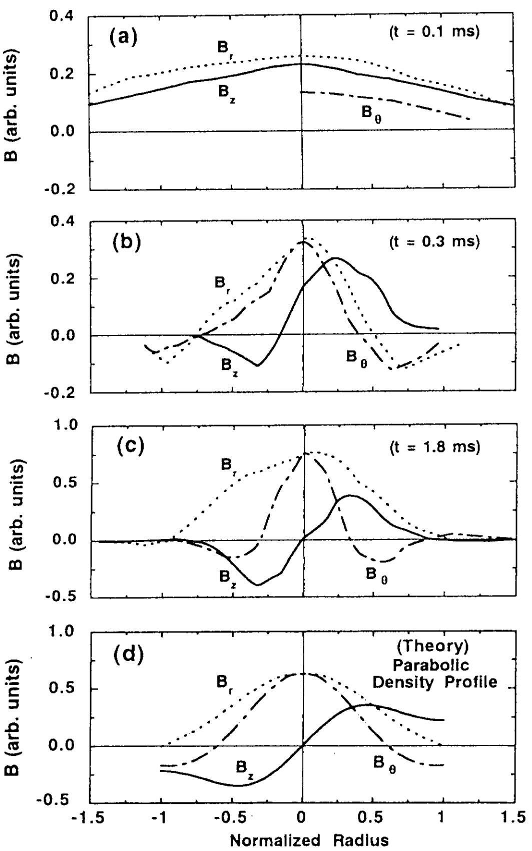

Fig. 9. Radial profiles of excited magnetic fields measured by the interferometric method at (a) $t = 0.1$ ms, (b) $t = 0.3$ ms and (c) $t = 1.8$ ms, and (d) calculated fields for $m = 1$ excitation.[84]

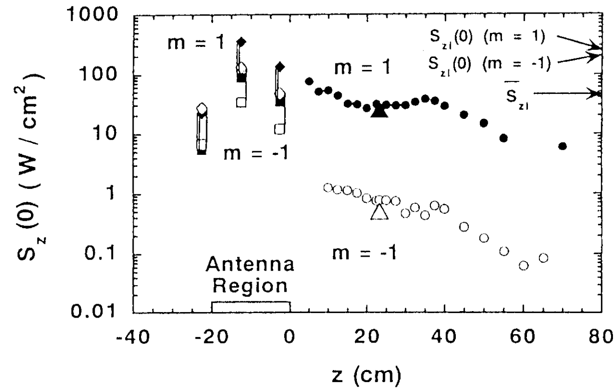

Fig. 10. Axial profiles of the Poynting vector $S_z(0)$ for $m = 1$ (closed symbols) and $m = -1$ (open symbols) excitations.[84] Here, circles, diamonds and boxes show values derived from case (i), where boxes represent values under the assumption of a standing wave, and triangles those derived from general expression of case (ii). The estimated initial energy fluxes, i.e., $S_{zi}(0)$ (plasma center) for the parabolic density profile for case (i) and mean value $\bar{S}_{zi}$, are shown for comparison.

several attempts to obtain the required plasmas, for example, by a new wave excitation method and by use of the optimized magnetic field configurations should be made. The control of the antenna wave number spectrum suggests[105,106] that matching this spectrum with the damping and/or generation spectrum related to the dispersion relation may be important. To generate a large-diameter plasma, a spiral antenna[107–110] (see Fig. 5(f); normally used as an ICP antenna) and a pair of 'serpentine' antennae[111] were tested, and a cusp configuration of the magnetic field with a spiral antenna[106,112,113] was also used successfully.

Next, we present our experimental results for the dispersion relation, spatial excited wave structures and energy flux of the HW, for the purpose of introducing typical wave studies. A one-turn helical antenna, which is similar to that shown in Fig. 5(c), on a 5-cm-diameter Pyrex tube for $m = 1$ and $m = -1$ excitations is used.[81] The RF power is 1–2 kW with a frequency of 7 MHz. Spatiotemporal magnetic probe measurements of wave amplitude, phase and polarization are useful for investigating the nature of the wave. Figure 7 shows the history of the dispersion relation of the excited wave on the (plasma angular frequency ω_p, parallel wave number $k_{/\!/}$) plane.[81,114] Here, the wave number was determined by use of the interferometric method, where both signals of a magnetic probe (a one-turn coil with ± 2 mm resolution), which is moving along the axial direction, and the antenna current for reference are input to a balanced mixer, and then into a boxcar integrator. Plasma density, calibrated using a 70 GHz microwave interferometer, was measured using an electric probe. For the case of a relatively small plasma radius of ~ 3 cm, $k_{/\!/}k_\perp$ is nearly proportional to ω_p^2/B on the basis of the dispersion relation (see eq. (6)), because the perpendicular wave number $k_\perp$ is larger than $k_{/\!/}$. This figure shows that in both modes of excitation, $m = 1$ and $m = -1$, the dispersion relation for the HW is not satisfied before the density jump, whereas this relation holds after the jump.

Figures 8 and 9 show the axial[81,114] (perpendicular component of the magnetic field) and radial[84] (three components) excited wave patterns, respectively, obtained by the above-mentioned interferometric method. A standing wave, localized near the antenna region, exists in the early phase, and a wave propagating along the axial direction with the radial structure of the HW is confirmed to exist after the density jump. For understanding the wave damping mechanism, wave energy flux measurements, in addition to the traditional measurement of wave amplitude as a function of the distance, are also important. The absolute value of the energy flux $\boldsymbol{S}$ can be a clue to the role of the HW as a source of high-density plasma production. This flux $\boldsymbol{S}$ of the HW is the same as the Poynting vector $\boldsymbol{P}$, because $\boldsymbol{T} = 0$, according to eq. (3), for the cold plasma. The axial z direction of the Poynting vector S_z in the cylindrical geometry is calculated[115] for two cases: (i) low rates of collisional and electron Landau damping, and (ii) a more general form, which does not change regardless of the occurrence of the above damping. Figure 10 (ref. 84) shows the derived S_z (0) at the plasma center as a function of the axial direction for the above two cases. It can be seen that most of the RF power injected in the antenna region after the density jump is carried by the HW, whose amplitude decreases during propagation in the axial direction.

5. Conclusions

Various propagating waves used to produce plasma were briefly described, along with methods of wave classification and the characteristics of dispersion relation, damping and cutoff, with emphasis on the applications of plasmas. Typical wave diagnostics were summarized, and wave characteristics and current research on electron cyclotron, helicon and surface waves, which have been extensively utilized in the plasma processing field, were presented. Finally, the helicon wave was taken as an example to introduce typical studies of propagating waves.

It is well understood that wave physics is crucial and is expected to play an increasingly important role in the field of plasma application, just as wave physics made a great contribution to the nuclear fusion field. Considering the individual requirements in the field of plasma application, we must seek a suitable wave along with an appropriate excitation system and experimental setup. In future studies, innovations and breakthroughs are needed in a continuous effort to incorporate hybrid fields and ideas; serendipity and inspiration are also needed. Furthermore, it is important to find a means to control parameters such as density, temperature, the velocity distribution function, space potential, directivity and uniformity to meet industrial requirements, in addition to developing advanced wave excitation methods and diagnostics.

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