INTERACTION OF A TRANSVERSE ELECTROMAGNETIC WAVE WITH A BOUNDED THERMAL PLASMA WITH AN EXTERNAL MAGNETIC FIELD

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1. Introduction

The interaction of a transverse electromagnetic (EM) wave with plasma electrons is an interesting problem in plasma physics. If the collision frequency of the electron is sufficiently large so that the plasma conductivity becomes local, then the problem is easy to treat and it is called *normal*. However, in certain conditions, there is non-negligible thermal motion of the electron, so that the response of the plasma should be described by a non-local conductivity and we call this case *anomalous skin effect*. Moreover, if the plasma is bounded by walls and the transit time of electron is comparable to the wave period, a modulation effect by the walls becomes important.

Weibel [1] studied the anomalous skin effect in semi-infinite plasma and Blevin *et al.* [2] has introduced the bounded plasma effect by assuming a symmetric source configuration. Recently, the semi-infinite problem is reminded by Turner [3] concerned with the problem of collisionless heating mechanism in inductively coupled plasma (ICP) discharge which is an important plasma source of semi-conductor fabrication device. The modulation effect by walls, when one side wall is conductor, was investigated by Yoon *et al.* [4]. Choi and Yoon [5] also adopted a right-going wave boundary conditions, and calculate the reflection, transmission, and absorption rate coefficients of the EM-wave.

In this work, we extend the model considered in Ref. [5] into the system to which an external magnetic field is applied.

2. Solution of Maxwell-Boltzmann Equations

Let us consider a transverse EM-wave with angular frequency, ω, incident on a plasma slab (Fig. 1). Some parts of the EM-wave are reflected at $z = 0$, transmitted, and absorbed by the plasma. We assume the normal injection of the wave, and wave angular frequency ω is much larger than ion plasma frequency and thus the ion motion is negligible.

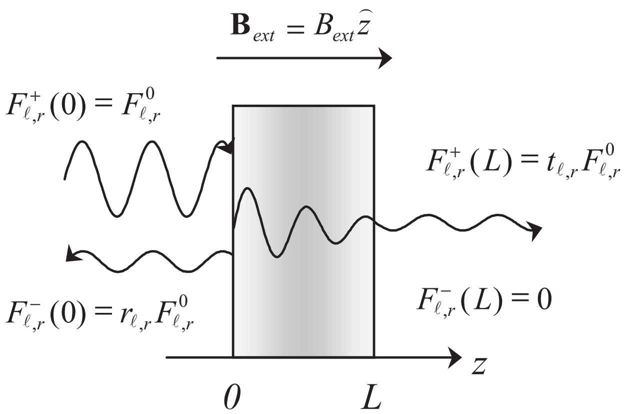

Fig. 1: Schematic diagram of the wave propagation.

The plasma is assumed to be a linear medium and a weakly ionized gas in which the electron collision with neutral atoms dominates Coulomb collisions. The plasma density and the electron temperature are assumed to be spatially uniform.

It is assumed that the wave is incident only from the left-hand side and thus there is no left-going wave in the region $z > L$. To describe the boundary conditions of the Maxwell equations, it is convenient to define the left(F^{-})- and right(F^{+})- going field quantities:

$$F^{\pm}_{\ell,r} \equiv \frac{1}{2}(E_{\ell,r} \pm B_{\ell,r}), \tag{1}$$

where L-and R-wave description was adopted:

$$E_{\ell,r} \equiv E_x \pm iE_y, B_{\ell,r} \equiv B_y \mp iB_x, \text{ and } J_{\ell,r} \equiv J_x \pm iJ_y. \tag{2}$$

With the above definition, the four equations of Faraday and Lenz laws can be transformed into the following equivalent equations:

$$\left(\frac{\partial}{\partial t} \pm c\frac{\partial}{\partial z}\right) F^{\pm}_{\ell,r}(z) = -\frac{\eta_0}{2} J_{\ell,r}(z), \tag{3}$$

where $\eta_0(= 4\pi/c)$ is the impedance of free space and c is the velocity of light.

Also the boundary conditions becomes

$$F^{+}_{\ell,r}(0) = F^{0}_{\ell,r} \text{ and } F^{-}_{\ell,r}(L) = 0. \tag{4}$$

Although the plasma current density is described through a non-local conductivity of plasma which has sharp boundaries, the perfectly reflecting boundary condition is a good approximation of electron reflection in usual bounded plasmas because the electron transition time is much smaller than the global loss time of plasma as long as $v_{th} > v_{i,th}$ where $v_{i,th}$ is the thermal velocity of ions as discussed in Ref. [4]. Moreover, if we utilize the boundary condition, the bounded plasma problem can be converted into an infinitely periodic problem. If we solve the model equations by Fourier transformation method, all quantities can be expressed as functions of $F^{0}_{\ell,r}$, and thus, coefficients of reflection($r_{\ell,r}$) and transmission($t_{\ell,r}$) becomes as

$$r_{\ell,r} = \frac{F^{-}_{\ell,r}(0)}{F^{0}_{\ell,r}} = \frac{\eta_{\ell,r} - 1}{\eta_{\ell,r} + 1} \text{ and } t_{\ell,r} = \frac{F^{+}_{\ell,r}(L)}{F^{0}_{\ell,r}} = \frac{S^{b}_{\ell,r}}{S^{a}_{\ell,r} + iL/2\kappa} \cdot \frac{2}{\eta_{\ell,r} + 1} \tag{5}$$

where normalized surface impedance,

$$\eta_{\ell,r} = \frac{2i\kappa}{L}\left[\frac{\left(S^{b}_{\ell,r}\right)^2}{S^{a}_{\ell,r} + iL/2\kappa} - S^{a}_{\ell,r}\right]. \tag{6}$$

Here

$$S^{a}_{\ell,r} = \frac{1}{2D^{0}_{\ell,r}} + \sum_{n=1}^{\infty} \frac{1}{D^{n}_{\ell,r}} \text{ and } S^{b}_{\ell,r} = \frac{1}{2D^{0}_{\ell,r}} + \sum_{n=1}^{\infty} \frac{(-1)^n}{D^{n}_{\ell,r}} \tag{7}$$

and

$$D^{n}_{\ell,r} = q_n^2 - \kappa^2 - \kappa_p^2 \frac{v_n}{v_{th}} Z_p\left(\frac{\omega \pm \omega_c + i\nu}{|q_n| v_{th}}\right). \tag{8}$$

Here $q_n \equiv n\pi/L$, $\kappa \equiv \omega/c$, $\kappa_p \equiv \omega_p/c$, $v_n \equiv \omega/q_n$, and Z_p is the plasma dispersion function[7].

Also the reflectance(R) and transmittance(T), and absorptivity(A) are expressed as

$$R_{\ell,r} = |r_{\ell,r}|^2, T_{\ell,r} = |t_{\ell,r}|^2, \text{ and } A_{\ell,r} = 1 - R_{\ell,r} - T_{\ell,r}. \tag{9}$$

3. Numerical Results and Discussions

Although dependence of the wave coefficients on various parameters can be studied through the present results, we present herein numerical results for the most interesting quantities of the absorptivity of R-wave focusing on the case that the electron cyclotron resonance(ECR) and cavity resonance effect.

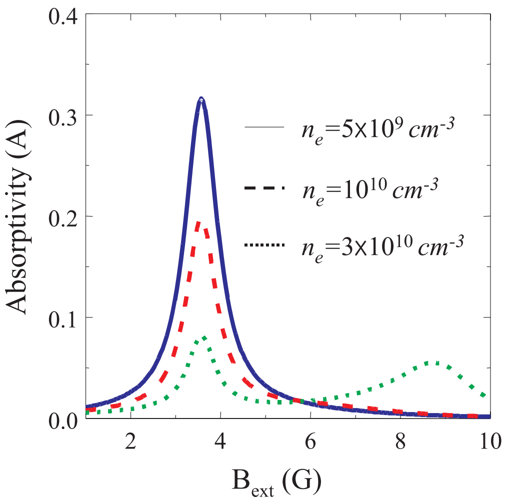

Fig. 2: Schematic diagram of the wave propagation. $L = 10\,cm$, $\omega/2\pi = 10\,MHz$, $T_e = 10\,eV$,$\nu/\omega = 0.1$ are used.

Figure 2 shows the functional dependence of absorptivity on the external magnetic field with several electron density. We can see the two peak in this result. The left hand side peak is due to the Doppler broadened electron cyclotron heating and the right hand side one indicates the cavity resonance effect. Using the used parameters, we can see that exact resonance magnetic field value, $B_{ecr} = 3.57\ G$.

The real peak is occurred at the magnetic field satisfying the Doppler broadened resonance condition: $qv_{th} = \omega_c - \omega$, where q is the typical wave number in plasma. Taking $q \sim q_0$, we can confirm the first peak is due to the ECR.

The cavity resonance is occurred when the following relation is satisfied:

$$L = (n/2)\lambda \ \ (n = 1, 2, 3, ...), \tag{10}$$

where λ is the wavelength in plasma. Finally, it is noticeable that the cavity resonance effect is not occurred in the case without external magnetic field because the real part of the wavenumber is always greater than its imaginary part.

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