AXIAL SYMMETRIC SURFACE WAVES IN TUBULAR MAGNETO-ACTIVE PLASMA COLUMN

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This paper is devoted to the dispersion properties of high-frequency axial symmetric potential surface waves propagating in a cylindrical waveguide structure. The structure is supposed to consist of a radially non-uniform plasma layer, partially filling a metal waveguide and immersed in an external axial magnetic field. The influence of the waveguide structure parameters, as well as the magnetic field value, on frequency, phase and group velocities, resonance damping of the surface waves is investigated both numerically and analytically.
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1. INTRODUCTION

To increase the plasma heating efficiency is one of the important problems in discharge maintenance by traveling surface waves (SWs) under low gas pressure [1, 2]. At those conditions, the collision mechanism of SW power transfer to a plasma becomes ineffective. It motivates the study of collisionless methods of plasma heating. One of them is resonant absorption of SWs that takes place in those plasma regions where the wave frequency is close to the upper hybrid one [3, 4]. The aim of this paper is to study the plasma parameter and external magnetic field influence on propagation and resonant damping of symmetric SWs in coaxial vacuum-plasma-vacuum-metal structures.

2. TASK STATEMENT

Let us consider high-frequency axial symmetric potential SWs that propagate along a cylindrical waveguide structure, which consists of a radially non-uniform plasma layer partially filling a metal waveguide with a radius R. The radial distribution of the plasma density is uniform, $n = n_0$, in the region $R_1 + d < r < R_2 - d$ and varies from n_0 to zero in the narrow ($d << R_1$) transition regions $R_1 < r < R_1 + d$ and $R_2 < r < R_2 - d$, where R_1 and R_2 are the internal and external radiuses of the plasma layer. An external steady magnetic field, H_0, is supposed to be directed along the waveguide structure axis. The plasma is considered to be a cold weakly collision medium with an effective electron collision frequency $\nu << \omega$, where ω is the wave frequency.

The dispersion relation of the considered surface waves has the following form

$$\frac{I_0(\chi_1 R_1)}{K_0(\chi_1 R_1)} \frac{\chi_1 Y_1 - k_3 T_1 + i\pi\eta_1 k_3 T_1 \chi_1 Y_1}{\chi_1 Z_1 - k_3 T_1 + i\pi\eta_1 k_3 T_1 \chi_1 Z_1} = \frac{I_0(\chi_1 R_2)}{K_0(\chi_1 R_2)} \frac{\chi_1 Y_2 - k_3 T_2 + i\pi\eta_2 k_3 T_2 \chi_1 Y_2}{\chi_1 Z_2 - k_3 T_2 + i\pi\eta_2 k_3 T_2 \chi_1 Z_2}, \quad (1)$$

where

$$Y_j = \varepsilon_1 \frac{I_0'(\chi_1 R_j)}{I_0(\chi_1 R_j)}, Z_j = \varepsilon_1 \frac{K_0'(\chi_1 R_j)}{K_0(\chi_1 R_j)}, T_1 = \frac{I_0'(k_3 R_1)}{I_0(k_3 R_1)},$$

$$T_2 = \frac{I_0'(k_3 R_2) K_0(k_3 R) - I_0(k_3 R) K_0'(k_3 R_2)}{I_0(k_3 R_2) K_0(k_3 R) - I_0(k_3 R) K_0(k_3 R_2)},$$

$$\varepsilon_1 = 1 - \frac{\Omega_e^2(\omega + i\nu)}{\omega[(\omega + i\nu)^2 - \omega_e^2]}, \qquad \varepsilon_3 = 1 - \frac{\Omega_e^2}{\omega(\omega + i\nu)},$$

$\eta_j = \left(d\varepsilon_1 / dr\right)^{-1}\Big|_{r_j}$; k_3 is the axial wavenumber; Ω_e, $\omega_e > 0$ are the electron plasma and cyclotron frequencies; $\chi_1 = k_3 \sqrt{\varepsilon_3 / \varepsilon_1}$ is the inverse depth of the SW penetration into the plasma; r_j are the points inside the transient regions, where the upper hybrid resonance $\varepsilon_1(r_j) = 0$ takes place, $r_j \approx R_j$; I_0 and K_0 are the modified cylindrical Bessel and McDonald functions of the zero order.

3. RESULTS AND DISCUSSION

Dispersion relation (1) describes propagation of two symmetric surface waves. The first wave propagates along the internal interface of the non-uniform plasma layer, whereas the second one does along the external border. General solution of dispersion equation (1) at arbitrary values of the waveguide parameters and external magnetic field can be obtained numerically only (fig. 1). Nevertheless, in some cases, analytical solution of equation (1) can be found.

3.1 LONG SURFACE WAVES

Firstly, we consider long symmetric SWs, when $k_3 R,\ \chi_1 R_2 << 1$. For the waves propagating at the internal border of the plasma layer, for an arbitrary ratio of the radiuses R_1 and R_2, one can write

$$\omega^2 = \omega_e^2 + \Omega_e^2 \left[1 - \frac{k_3^2 R_1^2}{2} \ln\frac{R_2}{R_1}\right],$$
$$\frac{\gamma}{\omega} = \frac{\nu}{2\omega} - \frac{\pi\eta_1}{R_1} \frac{k_3^4 R_1^4}{4} \ln\frac{R_2}{R_1}. \quad (2)$$

The presented expressions demonstrate that these waves are backward. Their frequency grows with an increase of the external magnetic field (fig. 1a) and weakly depends on the ratio of the external and internal radiuses of the plasma. It does not depend on value of the metal waveguide radius also (fig. 2a).

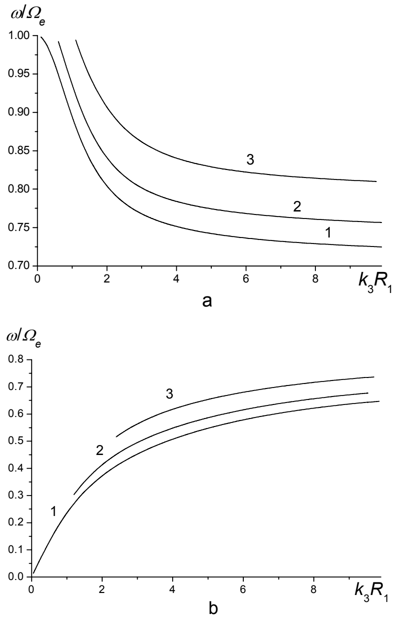

Fig.1. Influence of the external magnetic field on dispersion of the SWs propagating at the internal (a) and external (b) interfaces of the cylindrical plasma layer, in the case of R_2 / R_1 =2 and R / R_1 =2.1. The curves 1-3 correspond to ω_e / Ω_e =0; 0.3; 0.5

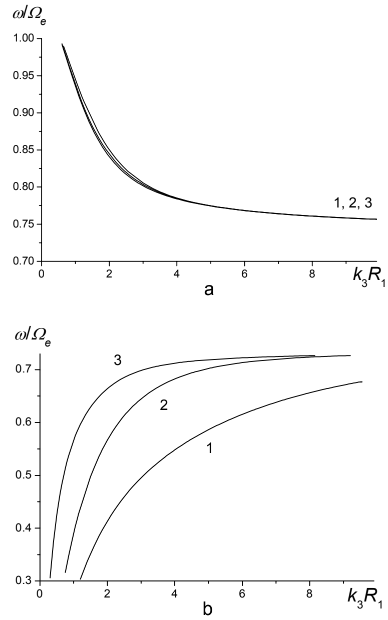

Fig.2. Influence of the metal on dispersion of the SWs propagating at the internal (a) and external (b) interfaces of the cylindrical plasma layer, in the case of R_2 / R_1 =2 and ω_e / Ω_e =0.3. The curves 1-3 correspond to R / R_1 =2.1; 2.3; 5.0

The frequency, ω, of the long SWs propagating at the external boundary of the plasma layer is described by

$$\omega^2 = \frac{\Omega_e^2}{2} k_3^2 (R_2^2 - R_1^2) \ln \frac{R}{R_2}. \quad (3)$$

It is necessary to mark, the condition $\chi_1 R_2 << 1$ holds for weak magnetic fields only, $\omega_e^2 << \Omega_e^2$. At that, the waves propagating at the external boundary are forward, in contrast to the waves propagating at the internal boundary of the layer (2). The frequency of these waves slightly depends on the magnetic field (fig. 1b) and is determined by the plasma layer width, as well as by the metal radius. As the metal comes to the plasma, the wave frequency decreases (fig. 2b). In the limit $R_2 = R$, the SWs do not exist at the external boundary of the plasma. In the absence of the metal, expressions for the frequency and damping rate for the waves at the external boundary become

$$\omega^2 = \frac{\Omega_e^2}{2} \frac{k_3^2 (R_2^2 - R_1^2)}{\ln k_3 R_2}, \frac{\gamma}{\omega} = \frac{\nu}{2\omega} - \frac{\pi \eta_2}{2} \frac{\Omega_e^4}{\omega^4} \frac{R_2^2 - R_1^2}{R_2^3 \ln k_3 R_2}. \quad (4)$$

Thus, the efficiency of resonant damping is proportional to the plasma layer width.

3.2 SHORT SURFACE WAVES

Now we consider short symmetric SWs, when $k_3 R_1,\ \chi_1 R_1,\ \chi_1 (R_2 - R_1) >> 1$. For the waves propagating at the internal border of the plasma layer,

$$\omega^2 = \frac{\Omega_e^2 + \omega_e^2}{2} \left[1 + \frac{1}{2 k_3 R_1} \right],$$
$$\frac{\gamma}{\omega} = \frac{\nu}{2\omega} \frac{\Omega_e^2 \omega^2 - \omega_e^4}{\omega^2 (\Omega_e^2 - \omega_e^2)} + \frac{(\omega^2 - \omega_e^2)^2}{\Omega_e^2 (\Omega_e^2 - \omega_e^2)} \pi |\eta_1| k_3. \quad (5)$$

In this region, SWs at the internal border of the plasma layer are backward with small group velocity and strong dependence on the external magnetic field (fig. 1a). They do not depend on the metal, as the long waves (fig. 2a).

Below, we study the influence of the metal waveguide on properties of the short SWs propagating at the external plasma boundary. Their frequency and damping rate look like

$$\omega^2 = \frac{1}{2} [-\omega_e^2 - 2 k_3^2 (R - R_2)^2 (\Omega_e^2 - \omega_e^2) + \sqrt{\omega_e^4 + 4 \Omega_e^4 k_3^2 (R - R_2)^2}\ ],$$
$$\frac{\gamma}{\omega} = \frac{\nu}{2\omega} \frac{\Omega_e^2 \omega^2 - \omega_e^4}{\omega^2 (\Omega_e^2 - \omega_e^2)} + \frac{(\omega^2 - \omega_e^2)^2}{\Omega_e^2 (\Omega_e^2 - \omega_e^2)} \pi \eta_2 k_3 cth[k_3 (R - R_2)]. \quad (6)$$

The resonant item in damping rate (6) increases as the metal comes close to the plasma, whereas the frequency decreases (fig. 2b). In the case, when the plasma bounds with the metal, the SWs do not propagate. In the metal waveguide absence, we obtain

$$\omega^2 = \frac{\Omega_e^2 + \omega_e^2}{2} \left[1 - \frac{1}{2 k_3 R_2} \right],$$
$$\frac{\gamma}{\omega} = \frac{\nu}{2\omega} \frac{\Omega_e^2 \omega^2 - \omega_e^4}{\omega^2 (\Omega_e^2 - \omega_e^2)} + \frac{(\omega^2 - \omega_e^2)^2}{\Omega_e^2 (\Omega_e^2 - \omega_e^2)} \pi \eta_2 k_3. \quad (7)$$

Thus, the frequency of SWs at the external border of the plasma layer increases from ω_e at $k_3 R_2 << 1$ up to the value $\sqrt{(\Omega_e^2 + \omega_e^2)/2}$ at $k_3 R_2 >> 1$ (fig. 1b).

3.3 PLASMA THICKNESS INFLUENCE

Influence of the ratio of the external and internal radiuses of the plasma layer, R_2 / R_1, on properties of the SWs is investigated also. It is shown both numerically (fig. 3a) and analytically (2) that an increase of the parameter R_2 / R_1 results in a decrease of the phase velocity of the waves propagating at the internal boundary of the layer. The phase velocity dependence for the waves at the external boundary of the layer on its width is more complicated. So, if the vacuum gap is wide enough, an increase of the layer thickness results in a growth of the SW phase velocity. However, at a fixed value of the metal radius, an increase of R_2 results in a decrease of the vacuum gap width. In this case, a decrease of the SW phase velocity by the metal coming to the plasma appears more essential, than its growth owing to the increase of the plasma layer width. Their relation for the case of a narrow waveguide is described by (3), and for the waveguide of a finite size is presented in fig. 3b (curve 4).

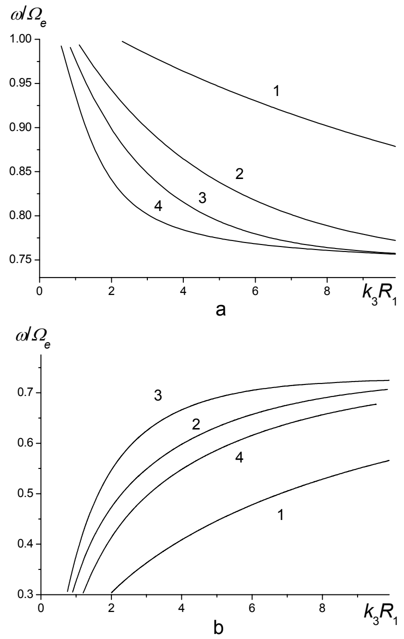

Fig.3. Influence of the plasma layer thickness on the dispersion of SWs propagating at the internal (a) and external (b) boundaries of the cylindrical plasma layer, in the case of R / R_1 =2.1 and ω_e / Ω_e =0.3. The curves 1-4 correspond to R_2 / R_1 =1.1; 1.3; 1.5; 2.0

CONCLUSIONS

In this paper, the dispersion properties and damping rates of the high-frequency axial symmetric potential surface waves propagating in the cylindrical metal waveguide partially filled with the radially non-uniform plasma immersed to the external steady axial magnetic field have been studied. It has been shown that the group velocity of the waves propagating at the internal and external interfaces of the cylindrical layer, have opposite signs. It has been obtained that the frequency of SWs, which can propagate at the internal plasma boundary, is greater than the frequency of SWs propagating at the external boundary. An increase in the external magnetic field has been shown to cause a growth of the wave frequency, whereas the area of axial wavenumbers, at which the waves exist, decreases.

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АКСИАЛЬНО-СИМЕТРИЧНЫЕ ПОВЕРХНОСТНЫЕ ВОЛНЫ В ТРУБЧАТОМ СТОЛБЕ МАГНИТОАКТИВНОЙ ПЛАЗМЫ

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В данной статье изучены дисперсионные свойства высокочастотных аксиально-симметричных потенциальных поверхностных волн, распространяющихся в цилиндрической волноводной структуре, состоящей из радиально неоднородного пламенного слоя, частично заполняющего металлический волновод и помещенного во внешнее аксиальное магнитное поле. Численно и аналитически исследуется влияние параметров волноводной структуры и внешнего магнитного поля на частоты, фазовые и групповые скорости поверхностных волн, а также на декременты их затухания.

АКСИАЛЬНО-СИМЕТРИЧНІ ПОВЕРХНЕВІ ХВИЛІ У ТРУБЧАТОМУ СТОВПІ МАГНІТОАКТИВНОЇ ПЛАЗМИ

Ю.О. Акімов, В.П. Олефір, М.О. Азарєнков

В роботі вивчено дисперсійні властивості високочастотних аксиально-симетричних потенціальних поверхневих хвиль, що розповсюджуються в циліндричній хвилеводній структурі, яка містить радіально неоднорідний плазмовий шар, що частково заповнює металевий хвилевод і знаходиться у зовнішньому аксіальному магнітному полі. Досліджено вплив параметрів хвилеводної структури та зовнішнього магнітного поля на частоти, фазові та групові швидкості поверхневих хвиль, а також на декременти їхнього загасання.