UDC 533.951

SURFACE CYCLOTRON X-MODES PROPAGATING ALONG A BOUNDARY OF UNIFORM PLASMA

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Received 19.06.2007

Propagation of surface cyclotron X - modes (SCXM) at the second harmonics of electron and ion cyclotron frequencies along interface of uniform semi-bounded plasma is under the consideration. It is proved both analytically and numerically that SCXM are the eigenmodes of a planar magneto-active plasma waveguide structure consisted of a metal wall with dielectric coating and uniform plasma filling. An external steady magnetic field is supposed to be oriented parallel to the plasma interface, so it is perpendicular to the group velocity of the considered extraordinary polarized waves. The influence of the plasma density on the SCXM dispersion has been studied. The theoretical investigation is carried out using the kinetic equation for plasma particles under the conditions of a weak plasma spatial dispersion and taking into the account ordinary case.

INTRODUCTION

At present time properties of electromagnetic bulk waves at harmonics of cyclotron frequencies are studied quite well (see, e.g. [1 – 3] and references therein). But one can't give such estimation on properties of surface cyclotron waves. At the same time investigation of different types surface waves is interesting in not only for solving definite radio-technical problems, but also for gas discharges study and other plasma applications. For instance papers [4 – 6] present results of experimental study of edge plasma effects connected with propagation of some types of surface waves in periphery of fusion plasma during regimes of ion cyclotron resonance heating. Just surface waves propagation is considered there as the some possible cause of such negative phenomena as plasma periphery heating, amplification of plasma-wall interaction, plasma contamination by impurity ions and so on. Last time different technological utilization of gas discharges becomes a branch of the most successive application of surface waves propagation. Elaboration and practical utilization of plasma sources based at surface waves propagation under the presence of external magnetic field is one of the foreground directions of development of the modern plasma technologies [7 – 11]. Thus investigation of surface cyclotron waves is important and actual problem of plasma physics.

Here dispersion and damping the surface cyclotron waves propagating across external magnetic field at harmonics of ion and electron cyclotron frequencies are studied in kinetic approach. It is shown that the direction of propagation of these waves correlates with the direction of Larmor precession of corresponding charged particles nearby plasma interface. In monograph [12] it is shown that under the indicated conditions surface cyclotron wave of extraordinary polarization can be eigenmodes, but doing that the only one component of the wave vector has been taken into the account for solving kinetic equation. Note that this dispersion was used in some papers, for example [13]. Therefore the aim of the present paper is to make definite correction to previous analytical expressions for surface cyclotron X-modes dispersion.

FORMULATION OF THE PROBLEM

Let's consider the model of semi-bounded completely ionized plasma, which consists of electrons and ions of one type and is restricted by dielectric in the plane $x = 0$. Influence of plasma non-uniformity on SCXM dispersion has been proved [10] to be weak, so we consider here the case of uniform plasma. External stationary magnetic field $\vec{B}_0$ is directed along axis , SCXM propagate along axis and they are skinning along axis, dependence on the coordinate z is absent.

We assume that plasma boundary is sharp, so that the value of transitional layer is considerably smaller than Larmor radius ρ_α (α indicates type of particles: $\alpha = i$ for ions, $\alpha = e$ for electrons). To solve the problem Vlasov-Boltzmann kinetic equation for plasma particles and Maxwell equations for electromagnetic field of these waves have been applied. Doing that we have supposed as well that plasma particles are described by the equilibrium Maxwell distribution function; the wave phase velocity is considerably smaller than the speed of light in the vacuum; the dependence of variable upon the coordinates and time is chosen in the following form:

. (1)

The kinetic equation for the disturbed part of the distribution function can be written in such way:

$$\times f_\alpha - \omega_\alpha \frac{\partial f_\alpha}{\partial \varphi} + e_\alpha \vec{E}\vec{\upsilon} \frac{\partial f_\alpha^{(0)}}{\partial \varepsilon} = 0, \quad (2)$$

$f(\vec{r},k) = f(k_1)\exp(ik_2 y - i\omega t)$, $k_\perp^2 = k_1^2 + k_2^2$, $i(\omega - k_\perp \upsilon_\perp \cos(\varphi))\times$

where $\upsilon_\perp = \sqrt{\upsilon_x^2 + \upsilon_y^2}$, φ is azimuthal angle in the velocity space, $\varepsilon \equiv \frac{m_\alpha \upsilon^2}{2}$, m_a – masses and e_a –charges of particles, $f_\alpha^{(0)}$ is the equilibrium distribution function. Solving kinetic equation (2), it is possible to find the Fourier coefficients of electric conductivity of plasma:

$$j_i(k_\perp) = \sigma_{ik}(k_\perp) E_k(k_\perp) + \frac{c}{4\pi} I_i(k_\perp), \quad (3)$$

where s_{ik} – tensor of electrical conductivity of non-bounded plasma, , I_i is non-differential part of the kernel of electrical conductivity tensor. Asymptotical values of $I_i(k_\wedge)$ are represented in [14]

Let's write down two components of the s_{ik}, which will be applied in the further consideration:

$$\sigma_{11} \approx \sigma_{22} = \sum_\alpha \sum_n \frac{in^2 \Omega_\alpha^2 e^{-y_\alpha} I_n(y_\alpha)}{4\pi(\omega - n\omega_\alpha) y_\alpha}, \quad (4)$$

$$\sigma_{12} = -\sigma_{21} = \sum_\alpha \sum_n \frac{n\Omega_\alpha^2 e^{-y_\alpha} [I_n(y_\alpha) - I_n'(y_\alpha)]}{4\pi(\omega - n\omega_\alpha)},$$

where $y_\alpha = \frac{k_\perp^2 \rho_\alpha^2}{2}$, $\omega_\alpha = \frac{e_\alpha B_0}{cm_\alpha}$, Ω_a – plasma frequency, $I_n(z)$ – is modified Bessel function.

From Maxwell set of equations one can find equations, which describe Fourier coefficient of tangential component of extraordinarily polarized E – wave, or in other words, X-mode. This set of equations has the following form:

$$\begin{cases} ik_\perp H_3 = \frac{H_z(0)}{2\pi} + ikE_2 - \frac{4\pi}{c} j_2; \\ ik_\perp H_3 = -\frac{E_y(0)}{2\pi} + ik_\perp E_2 - ik_2 E_1; \\ ik_2 H_3 = -ikE_1 + \frac{4\pi}{c} j_1 \end{cases}. \quad (5)$$

where $E_y(0)$ and $H_x(0)$ are the field of X-mode on the plasma border.

DISPERSION EQUATION

To obtain dispersion equation for the SCXM one can make reverse Fourier transformation of the equations (5). It can be done under the conditions of weak spatial dispersion of the plasma, because in this case one can simplify expression for components of plasma permeability tensor e_{ij}. But one can take into the account that in the ranges of electron and ion cyclotron frequencies the asymptotic behaviours of the tensor components are different. Therefore after the Fourier transformation one can derive the expression for impedance on the plasma boundary $E_y(0)/H_x(0)$:

$$\frac{E_y(0)}{H_z(0)} = \sum_{j=0}^{s-1} -\left[\frac{\partial \Delta(k_1)}{\partial k_1}\right]^{-1}\Bigg|_{k_j} \times$$

$$\times \left\{ \left[k_2 \varepsilon_{12}(k_j) - k_j \varepsilon_{11}(k_j)\right] \frac{E_y(0)}{H_z(0)} + \frac{k_2^2}{k} \right\}, \quad (6)$$

where $\Delta(k_1) = (k_1^2 + k_2^2)\varepsilon_{11}(k_1)$.

The next step in procedure of deriving the dispersion equation is finding expression of impedance on the boundary of dielectric region. It can be done by Fourier transform of equations (5) where first of all one can change diagonal elements of plasma permeability tensor by units and non-diagonal elements by zero. Then using boundary conditions in the form of equality of the calculated plasma impedance and vacuum region impedance one can derive the following dispersion equation:

$$1=\frac{k_2\varepsilon_{12}(i|k_2|)-i|k_2|\varepsilon_{11}(i|k_2|)+i|k_2|\varepsilon_d \mathrm{cth}(a_d|k_2|)}{2i|k_2|\varepsilon_{11}(i|k_2|)}-$$

$$-\frac{i|k_2|\varepsilon_d \mathrm{cth}(a_d|k_2|)+k_2\varepsilon_{12}(i|k_0|)}{(\partial\varepsilon_{11}/\partial k_1)|_{k_1=i|k_0|}(k_2^2-k_0^2)}, \qquad (7)$$

where ε_d – is permettivity of dielectric layer and a_d is its thickness.

It can be analytically solved for the cases of ion SCXM and electron SCXM The cases of the waves at the second cyclotron harmonics where considered in long wave approximation

$$k_\perp^2\rho << 1.$$

In the case of SCXM at the second harmonic of electron cyclotron frequency one can apply the following expressions for the components of plasma permeability tensor:

$$\varepsilon_{11}=\varepsilon_1-\frac{4\Omega_e^2 e^{-y_e} I_s(y_e)}{y_a\omega^2 h_e}; \quad \varepsilon_{12}=\varepsilon_2+\frac{i\Omega_e^2 y_e}{2\omega^2 h_e};$$

$$\varepsilon_1=1-\frac{\Omega_e^2}{\omega^2-\omega_e^2}; \quad \varepsilon_2=\frac{i|\omega_e|\Omega_e^2}{\omega(\omega^2-\omega_e^2)}, \qquad (8)$$

where $h_\alpha=1-\frac{2\omega_\alpha}{\omega}$.

But in the case of SCXM at the second harmonic of ion cyclotron frequency, which is considerably lower as compared with the electron cyclotron frequency, the asymptotic behaviors (8) already can't be use. In this case in the components permeability tensor it is necessary to take both ions and electrons items into the consideration:

$$\varepsilon_{11}=\varepsilon_1-\frac{4\Omega_i^2 e^{-y_i} I_s(y_i)}{y_a\omega^2 h_i}; \; \varepsilon_{12}=\varepsilon_2-\frac{i\Omega_i^2 y_i}{2\omega^2 h_i};$$

$$\varepsilon_1=1-\frac{\Omega_e^2}{\omega^2-\omega_e^2}-\frac{\Omega_e^2}{\omega^2-\omega_i^2};$$

$$\varepsilon_2=\frac{i|\omega_e|\Omega_e^2}{\omega(\omega^2-\omega_e^2)}-\frac{i\omega_i\Omega_i^2}{\omega(\omega^2-\omega_i^2)}. \qquad (9)$$

Analytical solutions of the dispersion equation SCXM can be presented in the following form:

$$h=\frac{\Omega_\alpha^2}{\omega^2}\frac{1-\varepsilon_2}{(\varepsilon_1-\varepsilon_2+1)^2}\rho_\alpha^2 k_2^2, \qquad (10)$$

For the limiting case $\Omega_\alpha^2 \approx \omega_\alpha^2$, and $\omega \approx 2\omega_\alpha$ the above expression may be written as:

$$h=-\frac{1}{6}\rho_\alpha^2 k_2^2. \qquad (11)$$

NUMERICAL ANALYSIS

Results of numerical analysis of the dispersion equation for the cases of SCXM at the second harmonics of electron and ion cyclotron frequencies are presented at the fig. 1, 2 respectively.

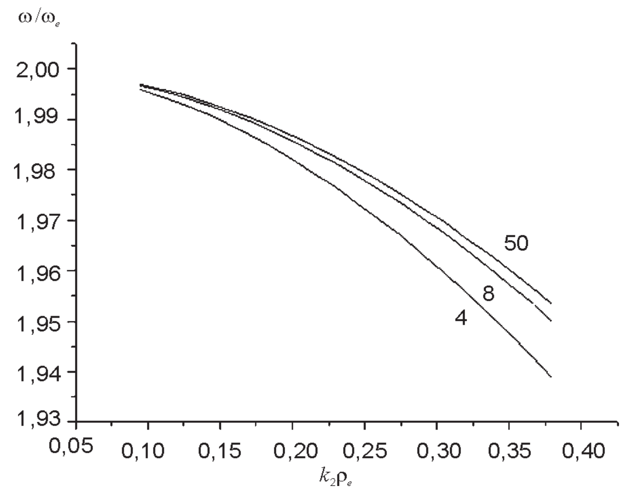

Fig. 1 Dispersion of the SCXM for the different values of the plasma density. Numbers on the plot represents relation between plasma and cyclotron frequencies Ω_e/ω_e.

Also we can analyze the dependence of SCXM frequency on thickness of dielectric layer. As one can see on fig. 3 decreasing of a_d leads first to the slow increasing of SCXM frequency and when a_d decreases below half of wavelength SCXM frequency rapidly closes to the resonance value $\omega/\omega_i \approx 2$.

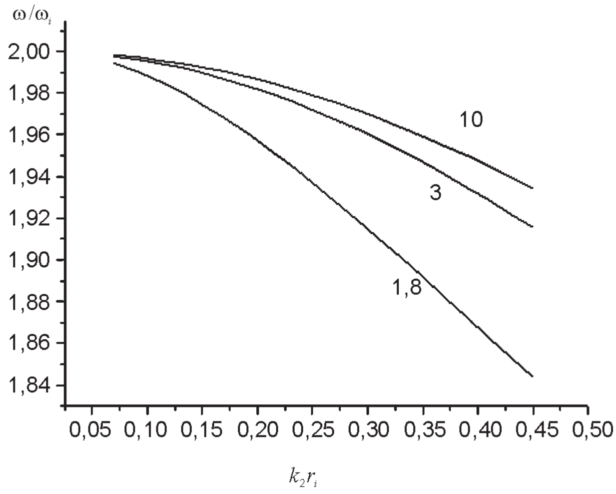

Fig. 2 Dispersion of the SCXM for the different values of the plasma density. Numbers on the plot represents relation between plasma and cyclotron frequencies Ω_i/ω_i.

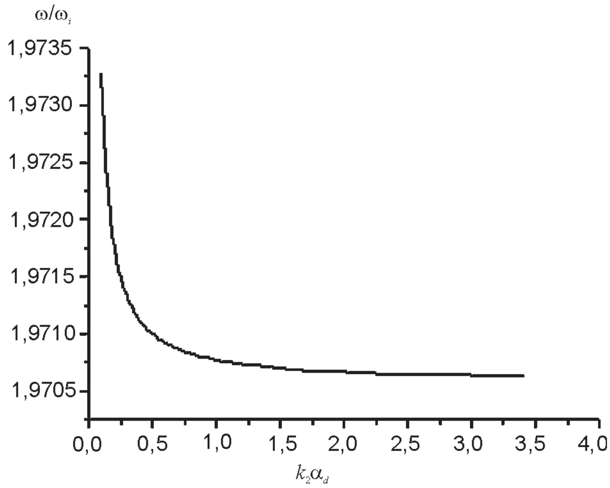

Fig. 3 Dependence of normalized SCXM frequency on thickness of dielectric layer. Relation between plasma and cyclotron frequencies $\Omega_i/\omega_i = 50$, $\varepsilon_d = 3$.

CONCLUSIONS

The directions of SCXM propagation is determined by Larmor rotation of positively charged ions and electrons in the magnetic field near the surface of plasma, respectively. So they are mutually opposite.

Thus it is shown that surface cyclotron X-modes can propagate in the waveguide structure composed by uniform semi-bounded plasma and dielectric under the condition, when external stationary magnetic field is oriented parallel to the plasma boundary and plasma dispersion is weak. They have extraordinary polarization, weakly attenuate, are unidirectional waves and their dispersion depends on the plasma density. Therefore these waves transfer energy only in one direction determined by Larmor rotation of the respectively charged particles.

Authors express acknowledgment of thanks to K.N. Stepanov and V.O. Girka for useful advices during discussion of this paper.

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ПОВЕРХНЕВІ ЦИКЛОТРОННІ X-МОДИ, ЯКІ ПОШИРЮЮТЬСЯВЗДОВЖ ГРАНИЦІ ОДНОРІДНОЇ ПЛАЗМИ

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У роботі розглядається поширення поверхневих циклотронних X-мод на другій гармоніці електронної та іонної циклотронної частоти вздовж границі однорідної напівобмеженої плазми. Аналітично та чисельно показано, що ці хвилі є власними модами плоскої магнітоактивної плазмової хвиле водної структури яка складається з металевої стінки з діелектричним покриттям та однорідного плазмового наповнення. Зовнішнє постійне магнітне поле спрямоване паралельно границі плазми, перпендикулярно груповій швидкості розглянутих незвичайно поляризованих хвиль. Було вивчено вплив щільності плазми на дисперсію поверхневих циклотронних X-мод. Теоретичне дослідження проведене з використанням кінетичного рівняння для плазми в умовах слабкої просторової дисперсії плазми.

ПОВЕРХНОСТНЫЕ ЦИКЛОТРОННЫЕ X-МОДЫ, РАСПРОСТРАНЯЮЩИЕСЯ ВДОЛЬ ГРАНИЦЫ ОДНОРОДНОЙ ПЛАЗМЫ

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В работе рассматривается распространение поверхностных циклотронных X-мод на второй гармонике электронной и ионной циклотронной частоты вдоль границы однородной полуограниченной плазмы. Аналитически и численно показано, что эти волны являются собственными модами плоской магнитоактивной плазменной волноведущей структуры состоящей из металлической стенки с диэлектрическим покрытием и однородного плазменного наполнения. Внешнее постоянное магнитное поле направлено параллельно границе плазмы, перпендикулярно групповой скорости рассматриваемых необыкновенно поляризованных волн. Было изучено влияние плотности плазмы на дисперсию поверхностных циклотронных X-мод. Теоретическое исследование проведено с использованием кинетического уравнения для плазмы в условиях слабой пространственной дисперсии плазмы.