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EXCITATION OF ION AZIMUTHAL SURFACE MODES IN A MAGNETIZED PLASMA BY ANNULAR FLOW OF LIGHT IONS

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Abstract—The excitation of ion azimuthal surface oscillations with extraordinary polarization by light ion beam is studied analytically. Beam-plasma system consists of a cylindrical metal waveguide filled partially by cold magnetized plasma and light ion flow rotating around the plasma column. Dependencies of the beam instability growth rate on the system parameters (plasma and beam densities, value of the external axial magnetic field, radius of the plasma column, width of the gap between the plasma column and the waveguide wall, absolute value and sign of the azimuthal wave number) are analyzed numerically.

1. INTRODUCTION

The efficiency enhancement of high-frequency electronic devices requires to solve a lot of problems. Among them, the most important problems are: studying the spectra of the eigen oscillations exciting in these devices, transportation of the charged particle flows interacting with these oscillations [1–3]. Plasma utilizing in such devices allows reaching a lot of important goals including the enhancement of the limiting current, the expansion of frequency spectrum of the excited oscillations, better controlling the excitation processes, etc. Interaction of the charged particle flows with plasma eigenwaves has already been used in plasma electronics to generate and amplify electromagnetic radiation for a long time [4–9]. Special attention is paid to studying the processes of wave excitation in magneto-active plasma waveguides. But until now the development of the beam-plasma instability theory has not been completed since the interaction of the charged particle

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beam with the eigenwaves of waveguides depends essentially on a large number of factors including the dispersion properties of the waves, their polarization, spatial distribution of wave fields, geometry and design features of the waveguide.

From this point of view, the study of annular charged particle beam interaction with the plasmas in the metal waveguides is considered as an actual problem [10, 11]. It is expected that the electronic devices with the annular beams have increased efficiency in comparison with the devices operating with longitudinal beams. For example, the instability growth rate and the efficiency of energy conversion in the annular free-electron lasers are larger (in $\gamma^{2/3}$ times) than the case of longitudinal ones [7]. In addition, the efficiency in the generators with longitudinal beams is limited by the length of the device. In the devices operated with the annular beams, the particles are rotated along Larmor orbits in the gap, which separates the chamber wall from the plasma column and transfer their energy to the electromagnetic wave so long as they reach the plasma surface as a result of the deceleration. In this way, the particles pass a pathway which is much larger than the sizes of the devices with longitudinal beams. First, it allows hoping to achieve higher efficiency in the devices operating with annular beams than the ones with longitudinal beams. Second, it gives a possibility to develop more compact electronic devices.

It is well known that surface wave excitation by charged particle beams has the interesting features [12]. The dispersion properties of the extraordinary polarized surface electromagnetic waves propagating along the azimuthal angle near the boundary of the plasma column are reviewed in [13]. These waves were called as Azimuthal Surface Waves (ASW). In the case of high-density plasma, $\Omega_e^2 > \omega_e^2$, Ω_e is Langmuir frequency and ω_e the electron cyclotron frequency, respectively. ASW can propagate in two frequency ranges: low frequency range (nearby the electron cyclotron frequency) and high frequency range (above the upper hybrid resonance). Possibility of resonant interaction of an annular electron beam with high frequency ASW was shown in [14]. Dependencies of the beam instability growth rate on the parameters of plasma-beam system (the plasma and beam densities, the azimuthal mode number, the value of the external steady axial magnetic field, the radius of the plasma cylinder and the thickness of the vacuum layer) are analyzed in detail. The excitation of ASW in the frequency range near the electron cyclotron frequency by annular electron beam was studied in [15]. It was shown [16] that the electromagnetic oscillations related to the ion component of the plasma can propagate with the negative azimuthal mode numbers in the cylindrical metal waveguide filled partially by a cold strongly magnetized plasma, $\Omega_e < \omega_e$. It was found that the minimum eigen frequency of these oscillations is several of the ion cyclotron frequencies. That is why the beam excitation of these waves was previously considered possible only due to their interaction with the beam particles oscillating at very high harmonics of the cyclotron frequency. Therefore, this process expects to be inefficient. However, in contrast to the oscillations at the frequencies within the electron cyclotron resonance range [13], the plasma oscillations of a certain ion kind can be excited by an ion beam consisted of another ion kind. If beam particles are lighter than the ions of basic plasma, the cyclotron frequency of the beam ions can be approximately equal to the eigen frequency of the ASW. Therefore, the excitation of the ASW by light ion beam can be much more efficient than one by the beam with the ions of the same kind. In this paper, we study, in detail, an initial stage of beam excitation of ion extraordinarily polarized ASW (XASW) in strongly magnetized plasma.

2. FORMULATION OF THE PROBLEM

Let us consider the geometry of the problem. The device is modeled by the metallic cylindrical waveguide with radius R_2. Cold magneto-active plasma column with radius R_1 is located coaxially inside the waveguide. Steady external magnetic field is directed along the axis of the system, $\mathbf{B}_0 \,\|\, \mathbf{Z}$. Fields of the extraordinarily polarized azimuthal surface wave are found from Maxwell equations. They are assumed to depend on the azimuthal angle φ and time t as follows: $\sim f(r)\exp(im\varphi - i\omega t)$. Annular ion beam, which is modelled as a flow of the oscillators with the same transverse momentum $p_{\perp 0}$ and zero axial momentum $p_z = 0$, is injected into the gap between the plasma column and the waveguide metal wall. We assume also that the plasma-beam system is compensated in the respect to both the electric currents and charges. The ion beam is described by the equilibrium distribution function: $f_0 = n_b \delta(p_\perp - p_{\perp 0})\delta(p_z)/(2\pi p_{\perp 0})$, where $p_{\perp 0} = m_b V_{\perp 0}\gamma$ is transverse momentum of the particles, $\gamma = \sqrt{1 + p_{\perp 0}^2 m_b^{-2} c^{-2}}$ the relativistic factor, and n_b the ion beam density. Electro-dynamical properties of the waveguide space where the beam rotates are described by the permeability tensor $\varepsilon_{ik}^{(b)}$ [14]. Let us write the expressions for the three components of the $\varepsilon_{ik}^{(b)}$ tensor, which are used in the further calculations:

$$\varepsilon_{11}^{(b)} = 1 + \frac{\Omega_b^2}{\omega\gamma} \sum_{s=-\infty}^{+\infty} s^2 \left[\frac{\left(J_s^2(x)\right)'}{(s-y)\, k_\varphi V_{\perp 0}} + \frac{\omega J_s^2(x)}{(s-y)^2 c^2 k_\varphi^2} \right]; \tag{1}$$

$$\varepsilon_{12}^{(b)} = \frac{i\Omega_b^2}{\omega\omega_b}\sum_{s=-\infty}^{+\infty} s\left[\frac{(J_s(x)J_s'(x))'}{s-y} + \frac{J_s(x)J_s'(x)}{(s-y)\,x} + \frac{J_s(x)J_s'(x)\omega V_{\perp 0}}{(s-y)^2c^2k_\varphi}\right]$$

$$= -\varepsilon_{21}^{(b)}; \tag{2}$$

$$\varepsilon_{22}^{(b)} = 1 + \frac{\Omega_b^2}{\omega\omega_b}\sum_{s=-\infty}^{+\infty}\left[\frac{2\,(J_s'(x))^2}{s-y} + \frac{2xJ_s'(x)J_s''(x)}{s-y} + \frac{(J_s'(x))^2\,V_{\perp 0}^2 y}{(s-y)^2\,c^2}\right], \tag{3}$$

where $\Omega_b^2 = 4\pi e^2 n_b m_b^{-1}$, $x = k_\varphi V_{\perp 0}\gamma/\omega_b$, $y = \omega\gamma/\omega_b$, $k_\varphi = |m|\,R_1^{-1}$, $J_s(x)$ is Bessel function, and a prime denotes the derivative with respect to the argument.

Solving Maxwell equations for the wave fields in the space occupied by the beam and taking into consideration the components of the tensor $\varepsilon_{ik}^{(b)}$ mentioned above, one can find a Bessel-type equation for the magnetic component of the wave field similar to the modified Bessel equation for the wave field in the plasma [13]. The azimuthal component of XASW electric field is expressed through the magnetic one. We use standard boundary conditions [14] to obtain the XASW dispersion relation. Then the equation describing the wave excitation by the beam has the typical form for such cases, $D^{(0)} = D^{(b)}$:

$$\frac{I_m'(\xi_1)k}{k_s I_m(\xi_1)} + \frac{\mu m k R_1}{\xi_1^2} = \frac{im\varepsilon_{12}^{(b)}}{\varepsilon_{11}^{(b)}\zeta_1\sqrt{\psi_b}} - \frac{J_m'(\zeta_1) - \Phi N_m'(\zeta_1)}{\sqrt{\psi_b}\,[J_m(\zeta_1) - \Phi N_m(\zeta_1)]}, \tag{4}$$

where $\Phi = [\frac{im\varepsilon_{12}^{(b)}}{\varepsilon_{11}^{(b)}\zeta_2}J_m(\zeta_2) - J_m'(\zeta_2)][\frac{im\varepsilon_{12}^{(b)}}{\varepsilon_{11}^{(b)}\zeta_2}N_m(\zeta_2) - N_m'(\zeta_2)]^{-1}$, $\mu = \frac{\varepsilon_2}{\varepsilon_1}$, $\zeta = kr\sqrt{\psi_b}$, $\zeta_1 = \zeta(R_1)$, $\zeta_2 = \zeta(R_2)$, $\psi_b = \varepsilon_{22}^{(b)} + (\varepsilon_{12}^{(b)})^2(\varepsilon_{11}^{(b)})^{-1}$, $\xi_1 = kR_1\sqrt{\varepsilon_1(1-\mu^2)}$, ε_j are the components of the dielectric permeability tensor of a cold magneto-active plasma [17]. Equation (4) can be solved analytically in the assumption of the following resonance condition:

$$\omega = \omega_0 + \delta\omega = N\omega_b\gamma^{-1} + \delta\omega, \tag{5}$$

here N is a positive integer, ω_0 the eigen frequency of the XASW in the absence of the beam, ω_b the cyclotron frequency of the beam particles, and $\delta\omega$ the frequency correction caused by the beam-plasma interaction, $|\delta\omega| \ll \omega_0$. Under the condition of resonant beam instability (5), the expression for the peak value of XASW growth rate can be represented in the following general form:

$$\mathrm{Im}(\omega) = \frac{\sqrt{3}}{2}\left(\frac{\alpha\Delta\Omega_b^2 N^2 J_N^2(|m|)V_{\perp 0}^2}{\gamma\, c^2}\right)^{\frac{1}{3}}\left(\frac{\partial D^{(0)}}{\partial\omega}\right)^{-1/3}. \tag{6}$$

Here and hereinafter $\alpha = n_b/n_p$ is the ratio of the beam to plasma densities ($\alpha \ll 1$).

3. RESULTS OF NUMERICAL ANALYSIS OF THE DISPERSION RELATION

Excitation of XASW with azimuthal wave numbers $m = -2, -3, -4$ in a neon plasma by alpha-particles beam is studied numerically. Growth rates of beam instability normalized by the ion plasma frequency, $\mathrm{Im}(\omega)/\Omega_i$, are counted along the ordinate axis. Dimensionless abscissa is chosen in the form $\theta = \omega_i/\Omega_i$, since the analytical expression for XASW eigen frequency obtained in [16] contains this combination as a principal parameter. Thus, one can say that the plots show the dependence of growth rates on the external magnetic field. The plasma density is chosen to be sufficiently large, $c/(\Omega_i a) = 5/6$. It allows enhancing the role of the term in the expression for the tensor component $\varepsilon_{22}^{(b)}$ (3), which is proportional to $V_{\perp 0}^2$ and responsible for the beam excitation. By calculating the plots in Figures 1 and 3, the beam density is assumed to be sufficiently small, $\alpha = 10^{-6}$.

Conditions of XASW instability in dependence on the azimuthal mode number are compared in Fig. 1. Dependencies of growth rates are shown for the XASW with azimuthal mode numbers $m = -2$ (Fig. 1(a)), $m = -3$ (Fig. 1(b)), $m = -4$ (Fig. 1(c)). The relative width of the layer between the plasma and the metal chamber is assumed to be equal, $\Delta = R_2/R_1 - 1 = 0.1$.

Let us discuss the plots in Fig. 1(b) in detail. The highest peak on the plot is a result of the XASW interaction with the alpha particles oscillating at the first cyclotron harmonic of helium. Therefore, it is designated as $N = 1$. The maximum value of the growth rate $\mathrm{Im}(\omega) \approx 1.9 \times 10^{-3}\Omega_i$ is obtained for $\theta \approx 0.21$. In this case, the real part of the wave frequency is close to the fifth ion cyclotron harmonic of neon, $\mathrm{Re}(\omega) \approx 4.9\omega_i$. Velocity of alpha particles in this case is $V_{\perp 0} \approx 0.255c$, and the relativistic factor is equal to $\gamma \approx 1.034$, indicating a very weak relativism of the beam. Maximum on the second peak, $\mathrm{Im}(\omega) \approx 1.05 \times 10^{-3}\Omega_i$, is reached at $\theta \approx 0.12$. This excitation is caused by the interaction of XASW with the beam particles oscillating at the second cyclotron harmonic of helium, which is concluded from the real part of the frequency value, $\mathrm{Re}(\omega) \approx 9.8\omega_i$. The decrease of the external magnetic field (accompanied with corresponding decrease of beam velocity) is the reason of the observation in Fig. 1, i.e., decrease of the growth rate in the peaks $N = 2$ and $N = 3$ compared with the peak $N = 1$. Finally, the third peak shown in Fig. 1(b), $\mathrm{Im}(\omega) \approx 0.25 \times 10^{-3}\Omega_i$ is caused by the interaction of neon plasma with the third cyclotron harmonic of helium, $\mathrm{Re}(\omega) \approx 15.0\omega_i$ (compare with the second peak). In this case, $\theta \approx 0.09$, $V_{\perp 0} \approx 0.114c(\gamma \approx 1.007)$.

Just as in the case of electron ASW excitation [14], the oscillations

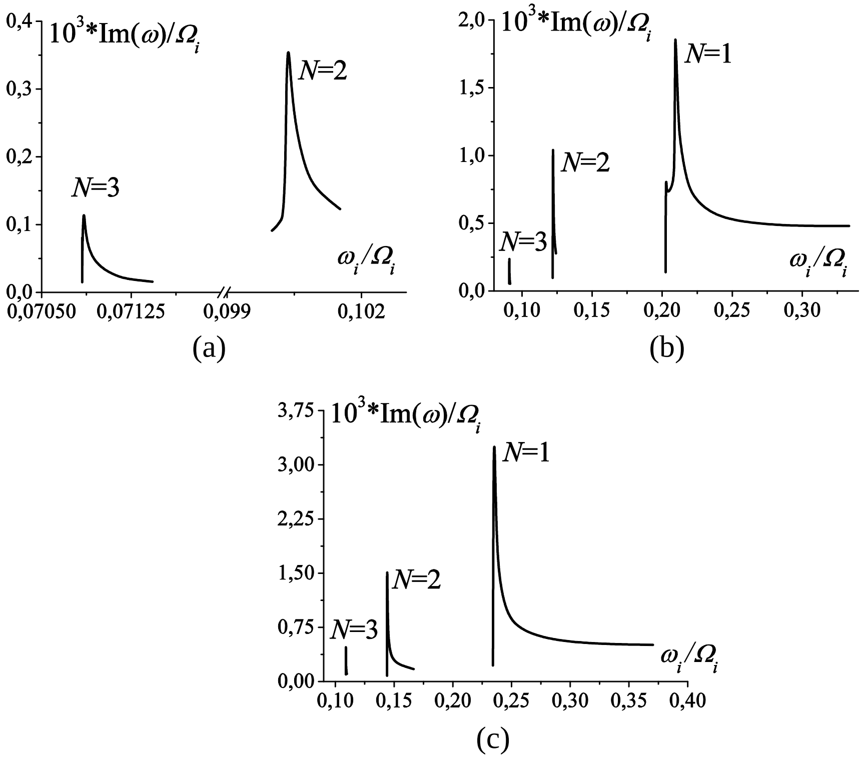

Figure 1. (a) The XASW growth rates normalized by plasma frequency of the basic plasma, $\mathrm{Im}(\omega)/\Omega_i$, versus the normalized external axial magnetic field $\theta = \omega_i/\Omega_i$. $\alpha = 10^{-6}$, $\Delta = 0.1$, $m = -2$. (b) The same as in Fig. 1(a), but for $m = -3$. (c) The same as in Fig. 1(a), but for $m = -4$.

of the ion plasma component with higher azimuthal mode numbers are excited with higher growth rates. The maxima of the peaks in Fig. 1(c) are higher and achieved for stronger magnetic fields than the mode $m = -3$: at points (0.235, 3.27), (0.144, 1.51), (0.11, 0.48), respectively. The maxima of the peaks in Fig. 1(a) are lower and achieved for weaker magnetic fields than for the mode $m = -3$: $\mathrm{Im}(\omega) \approx 0.356 \times 10^{-3}\Omega_i$ as a result of the XASW interaction with the alpha particles, which oscillate at the second cyclotron harmonic of helium, in this case $\theta \approx 0.1$; $\mathrm{Im}(\omega) \approx 0.114 \times 10^{-3}\Omega_i$ for the interaction of XASW with alpha particles, which oscillate at the third cyclotron harmonic, while $\theta \approx 0.07$. Let's note that a possibility of beam excitation for the XASW with $m = -2$ when $N = 1$ is not indicated. This is explained by the fact that the XASW frequency increases with azimuthal mode number $|m|$, but even the XASW frequency for $m = -3$ slightly exceeds the lower boundary of the frequency range where the waves propagate. Therefore, the propagation of XASW with $m = -2$ is impossible for the considered values of the beam-plasma parameters.

The plot in Fig. 2 is calculated for the same values of the parameters of the beam-plasma system, as in Fig. 1(b), except the beam density, which is equal to $\alpha = 10^{-3}$ in this case. Apparently, the change of beam density does not affect the positions of the peaks. The peaks become wider, and overlapping of different resonances is observed with increasing beam density. Increase in the beam density by three orders up to $\alpha = 10^{-3}$ leads, in Fig. 2, as follows from the analytical solutions (Eq. (6)), to increasing the growth rate by the order: the peak height for the $N = 1$ is $\mathrm{Im}(\omega) \approx 21.2 \times 10^{-3}\Omega_i$.

A plot of the growth rate dependence on θ is calculated in Fig. 3 for the same values of the beam-plasma parameters, as in Fig. 1(b), except the width of the vacuum gap, which is assumed to be equal, $\Delta = 0.135$ in this case. Ceteris paribus the increasing of the gap width leads to a shift of the peaks to the range of stronger external magnetic field: they are observed at $\theta \approx 0.096$, 0.13, and 0.22, respectively. The longitudinal (with respect to the beam velocity) wave electric field is zero at the plasma surface, and the trajectories of the beam particles move away from the metal chamber with the broadening of the vacuum gap. That is why the efficiency of alpha particle interaction with the wave increases, and the growth rates become greater than that of the

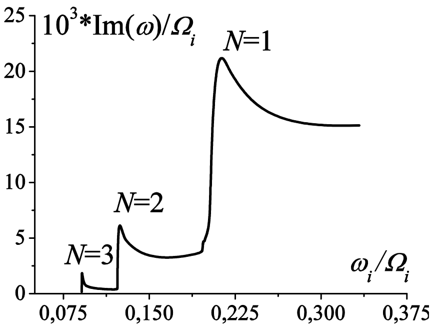

Figure 2. The same as in Fig. 1(b), but for more dense beam, $\alpha = 10^{-3}$.

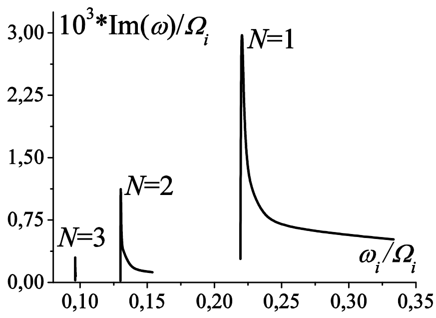

Figure 3. The same as in Fig. 1(b), but for more wide beam gap, $\Delta = 0.135$.

case $\Delta = 0.1$.

Let us estimate a possibility of experimental realization of the investigated phenomenon. As an example, we choose a point on the top of the first peak in Fig. 1(b). Let the radius of the laboratory plasma be 0.1 m. Then the condition $c/(\Omega_i a R_1) = 5/6$ used in our calculations needs the density of neon plasma: $n_{Ne} \approx 1.5 \times 10^{20}\,\mathrm{m}^{-3}$. Corresponding beam density is $n_{He} \approx 1.5 \times 10^{14}\,\mathrm{m}^{-3}$. The maximum in the first peak on the plot is realized for the external magnetic field $B_0 \approx 160\,\mathrm{T}$. A non-relativistic beam, $V_{\perp 0} \approx 0.255c$, is required to excite the XASW. In this case, the wave is excited with the growth rate $\mathrm{Im}(\omega) \approx 6.85 \times 10^6\,\mathrm{s}^{-1}$ at the frequency of $\omega \approx 3.69 \times 10^9\,\mathrm{s}^{-1}$.

We are aware of the fact that the requirement of such a large value of B_0 is the weakest point of the proposed project. That is why we looked for the conditions of the XASW excitation when the magnetic field induction could be as small as possible. As an example, we consider the excitation of the XASW third azimuthal mode in helium plasma by proton beam. Let the radius of the laboratory plasma be 0.1 m. Then the condition $c/(\Omega_i a R_1) = 1.6$ gives the following density of helium plasma: $n_{He} \approx 8 \times 10^{18}\,\mathrm{m}^{-3}$. Let assume that the density of the proton beam is by six orders of magnitude smaller, $n_p \approx 8 \times 10^{12}\,\mathrm{m}^{-3}$. Effective interaction of the wave with the third cyclotron harmonic is realized for the $B_0 \approx 20\,\mathrm{T}$. Although this is also a very strong magnetic field, the method of its production is well known [18], and it is enough to produce it in a small volume of the $3 \times 10^{-3}\,\mathrm{m}^3$ order. Recall also that the relativistic beam is not required for the wave excitation under these experimental conditions: $V_{\perp 0} \approx 0.08c$. In other words, it is a beam of protons with energies $W = 0.5 \times 10^{-12}\,\mathrm{J}$ which carries an electric current $I \approx 0.03\,\mathrm{A}$ with a density of $32\,\mathrm{A/m}^2$. Required proton beams can be obtained, for example, in the linear proton accelerators with focusing the electron beam [19] or the linear accelerators such as LEDA [20]. In this case, the wave is excited with the growth rate of $7 \times 10^5\,\mathrm{s}^{-1}$ at the frequency $6 \times 10^9\,\mathrm{s}^{-1}$.

4. DISCUSSION OF THE RESULTS

In the paper, we investigate the possibility of excitation of ion XASW with negative azimuthal mode number in strongly magnetized plasma by annular beam of light ions. Numerical calculations confirm that the resonance interaction of the beam with this type of surface waves can be realized in sufficiently strong external magnetic field. Effective excitation appears to be possible for the XASW when the normalized frequency is close to multiples of the mass ratio of the main plasma ions and the beam ions. The results of the numerical analysis are in a good agreement with the analytical calculations. Growth rate of the XASW resonant beam instability is shown to increase with increasing azimuthal mode number, the width of the gap Δ between the plasma column and waveguide wall, and the beam density.

Though the relativistic beam is not needed for the XASW excitation, the demands on the external magnetic field appear rigid enough to realize the conditions of the excitation. This is explained by the following reason: the third term in the expression (3) for $\varepsilon_{22}^{(b)}$ (it is proportional to $V_{\perp 0}^2$) is responsible for the excitation of the waves. In the case of a weak magnetic field, the velocity of beam particles $V_{\perp 0}$ appears small, and first two terms prevail in expression (3). Therefore, the excitation of XASW does not take place.

Excitation of XASW by annular ion beam is characterized by the following feature. The beam rotates in an external magnetic field in a gap between the plasma column and the metal chamber. Therefore, the beam velocity is defined by an induction of the external magnetic field and radii of the plasma column and the metal chamber, $\omega_i R_1/\gamma < V_{\perp 0} < \omega_i R_2/\gamma$. When the beam radius is closer to the metal chamber radius, more kinetic energy can be transferred into electromagnetic wave before beam reaching the plasma surface due to its deceleration. On the other hand, when the beam is closer to the metal chamber, the electric field of the excited mode is weaker. Thus the efficiency of beam-plasma interaction is lower also.

Higher efficiency can be expected for wider gap Δ between the plasma column and the metal wall of the waveguide where the ion beam rotates. The increase in Δ leads also to substantially increasing the growth rate of the ion XASW excitation that was observed also in the case of electron ASW [14].

The value of the induction of external magnetic field B_0 is characterized by parameter θ in our problem. Dependence of $\mathrm{Im}(\omega)$ on B_0 is non-monotonic one, since the most effective beam excitation of the XASW occurs for B_0 values when XASW eigen frequency crosses curves $\omega = \omega_b N/\gamma$ (see the condition (5)). In general, smaller B_0 requires higher harmonics of beam ion cyclotron frequency for beam particle oscillations to provide resonant interaction with XASW, which leads to smaller growth rates.

Excitation of different types of surface waves (SW) is actively studied theoretically and widely applied to develop different electronic devices (the generators of electromagnetic power (see, e.g., [9–11, 21]), antennas etc.). Paper [22] presents novel results of studying the properties of SW propagating in photonic band gap materials. Advantages of such materials are their robustness, simple fabrication and ability to operate in a wide frequency range, namely from microwave up to optical frequencies. Results of experimental study of a fluorescent tube as monopole plasma antenna are represented in [23]. It is important to add that utilization of SW in radar systems is commonly used as an effective and low-cost method, which can provide over-the-horizon surveillance of surface objects. Advantage of the SW radars consists in their ability to suppress the ionospheric clutters, which exert a main negative impact on operation of radars' systems [24].

The presented results can be of interest to solving different tasks in the field of plasma electronics. The XASW energy can easily radiate from the waveguide. If one makes a narrow ($\varphi_0 \ll \pi$) axial slot in the metal chamber of the waveguide, then XASW energy will radiate through it into the open space. As shown in [25], for the case of electron ASW with different values of the azimuthal mode number, the damping rates caused by their radiation are less than growth rates of beam instability in the range of small effective wave numbers. Note that the flux of electromagnetic radiation can be controlled by varying the azimuthal size of the slot, since the damping rate caused by radiation of the energy is proportional to φ_0 in linear approximation.

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