EXCITATION OF COUPLED ELECTROMAGNETIC AND POTENTIAL WAVES IN INHOMOGENEOUS PLASMA CYLINDER IN MAGNETIC FIELD

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1. In helicon sources the discharge is produced and sustained by the RF electric field with the frequency located between the cyclotron frequencies of electrons and ions, $\omega_{Ci} << \omega << \omega_{Ce}$. The antennas positioned outside the plasma column generate this field. Along with the electromagnetic waves (whistlers, or helicons) the quasi-electrostatic (QE) oscillations (Trivelpiece-Gould modes) are excited due to the coupling between the electric fields of these modes at the plasma boundary (surface conversion of modes) or deep in the plasma where their wave numbers coincide (volume conversion). The reviews of research into absorption of RF fields in helicon sources are presented in papers [1,2].

If the amplitude of the electron oscillation velocity in the pumping electric field across a steady magnetic field B_0 exceeds the ion sound velocity, then in a helicon source a kinetic ion-sound parametric instability is excited that may lead to turbulent heating of electrons and ions, absorption of pumping field energy and discharge sustainment [3,4]. Similar parametric instability in helicon sources is discovered recently [5,6].

The modes considered are purely electronic if $\omega >> \omega_{LH}$, where ω_{LH} is the frequency of the lower hybrid resonance, $\omega_{LH}^2 = \omega_{Ce}\omega_{Ci}/(1+q)$, $q = \omega_{Ce}^2/\omega_{pe}^2$. For $\omega \le \omega_{LH}$ the properties of the helicon discharge depend on the ion component essentially. Specifically, the papers [6,7] have shown that in this case the temperature and density of electrons as well as the temperature of ions can be several times increased. The present work is devoted to the theoretical study of the effect of ions on the absorption of electromagnetic fields in a helicon source in the frequency range $\omega \sim \omega_{LH}$.

2. Let us model such a source as an endless nonuniform plasma cylinder immersed in the axial magnetic field. The antenna is modeled by a surface current with the electric current density $j^{ext} = \mathrm{Re}\left(j_\phi e_\phi + j_z e_z\right)\delta(r - r_a)\exp(i\psi)$, where $\psi = k_\parallel z + m\phi - \omega t$. The quantities j_ϕ and j_z are related via the closure condition $k_\parallel j_z + (m/r_a) j_\phi = 0$. In this case the solution of Maxwell's equations through the WKB technique is proportional to $\exp\left(i\int k_r dr + i\psi\right)$, where the radial wavenumber k_r is found from the eiconal equation.

When the inequality $N_\parallel^2 >> \varepsilon_e$ holds, where $\varepsilon_e = 1 + \omega_{pe}^2/\omega_{Ce}^2$, then the wavenumbers of a QE mode and a helicon are not coupled and are determined from the equations

$$k_r^2 = k_\parallel^2 \frac{(\omega_{Ce}/\omega)^2}{1+q} \frac{1 - i\nu_e/\omega}{1 + i(\nu_e/\omega)/(1+q) - \omega_{LH}^2/\omega^2}, \quad (1)$$

$$k^2 = \frac{\omega_{pe}^4\omega^2}{\omega_{Ce}^2 k_\parallel^2 c^4}\left[1 + 2\frac{\omega_{pe}^2}{\omega_{Ce}^2 N_\parallel^2}\left(1 - i\frac{\nu_e}{\omega} - \frac{1}{2}\frac{\omega_{LH}^2}{\omega^2}\right)\right] - \frac{\omega_{pe}^2\omega_{LH}^2}{c^2\omega_{Ce}^2} \quad (2)$$

Here $k^2 = k_r^2 + k_\phi^2 + k_z^2$, $k_\phi = m/r$, $\nu_e = \nu_{ei} + \nu_{en}$ is the sum of electron-ion and electron-neutral collision rates $(\nu_e << \omega)$, ion collisions are neglected. Expression (2) for a helicon is obtained under the conditions $\omega_{pe}^2 >> \omega_{Ce}^2 >> \omega^2$. When the condition $N_\parallel^2 >> \varepsilon_e$ holds, the QE wavenumber and its damping due to collisions exceed those for a helicon considerably. As it follows from (1), the propagation of the QE mode is possible for $\omega > \omega_{LH}$. Its damping is especially large for $\omega \approx \omega_{LH}$. It follows from (2) that the presence of ions has a weak effect on the helicon dispersion for $\omega \sim \omega_{LH}$, if $N_\parallel^2 << \omega_{pe}^2/\omega_{LH}^2$.

When $N_\parallel^2 \sim \varepsilon_e$, then the helicon and the QE mode are coupled together, and their radial wavenumbers k_r are determined by the expression $k_r^2 = k_\pm^2$, where

$$k_\pm^2(r) = k_0^2\left(b \pm \sqrt{b^2 - d}\right), \quad (3)$$

$$k_0^2 = \omega_{pe}^2/(c^2\xi), \quad \xi = 1 - \omega_{LH}^2/\omega^2,$$

$$2b = \frac{N_\parallel^2}{\varepsilon_e} - \xi - \frac{1}{1+q} - i\frac{\nu_e}{\omega}\left[\frac{N_\parallel^2}{\varepsilon_e} - \xi + \frac{1/\xi}{1+q}\left(\frac{N_\parallel^2}{\varepsilon_e} - \frac{1}{1+q}\right)\right],$$

$$d = \frac{\xi}{1+q}\left[1 - i\frac{\nu_e}{\omega}\left(1 + \frac{1/\xi}{1+q}\right)\right].$$

Here it was assumed that $\nu_e/\omega << |\xi|, 1$. From (3) it follows that for $\omega < \omega_{LH}$ only a helicon can propagate, $k_r^2 = k_-^2 > 0$, and $k_+^2 < 0$ for $\nu \to 0$. When, however, $\omega > \omega_{LH}$, then both modes can propagate in the region with the density $n(r) < n_c$, n_c being determined from the condition $b^2 = d$ (for $\nu/\omega \to 0$), i.e., $N_\parallel^2/\varepsilon_e = \left(\sqrt{\xi} + 1/\sqrt{1+q}\right)^2$ for $r = r_c$. The wavenumbers of both modes coincide at $r = r_c$, $k_r^2 = k_c^2$, where

$$k_c^2 = \omega_{pe}^2/\left(c^2\sqrt{\xi}(1+q)\right). \quad (4)$$

In the vicinity of this point we have

$$k_\pm^2 = \frac{\omega_{pe}^2}{c^2\xi}\left(\sqrt{\frac{\xi}{1+q}} \pm \sqrt{\frac{r_c - r}{a_n}s - i\frac{\nu_e}{\omega}p}\right), \quad (5)$$

where $a_n = \left(d\ln n(r)/dr\right)^{-1}|_{r=r_c}$ and

$$s = \frac{N_\parallel^2}{\varepsilon_e} - \frac{q}{1+q}\left(\frac{N_\parallel^2}{\varepsilon_e} + \frac{\omega_{LH}^2}{\omega^2} - \frac{2\xi}{1+q}\right),$$

$$p = \sqrt{\frac{\xi}{1+q}}\left[\frac{N_\parallel^2}{\varepsilon_e} - \xi + \frac{1/\xi}{1+q}\left(\frac{N_\parallel^2}{\varepsilon_e} - \frac{1}{1+q}\right)\right] - \frac{\xi}{1+q}\left(1 + \frac{1/\xi}{1+q}\right)$$

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Hence it follows that $k_\pm^2$ is a complex number (for $\nu_e/\omega \to 0$) when $r < r_c$ with $a_n < 0$, or when $r > r_c$ with $a_n > 0$.

For $r \to r_c$, as it follows from (5), the damping increases.

At $r \approx r_c$ the WKB technique fails if the inequality $|r - r_c|^{3/2} >> \left(|a_n|/k_c^2\right)^{1/2}$ is violated. In this case one should use the solution of Maxwell's equations in the form $E \propto \exp[\pm ik_0(r - r_c)]Ai(t)$, where the argument of the Airy function is equal to $t = \left(k_0^2 Q/4a_n\right)^{1/3}(r - r_c)$, where

$$Q = \frac{N_\parallel^2}{\varepsilon_e} - \frac{q}{1+q}\left(\frac{N_\parallel^2}{\varepsilon_e} - \frac{1}{1+q} + \frac{\omega_{LH}^2}{\omega^2} + \frac{1}{\sqrt{\xi(1+q)}} - \frac{2\omega_{LH}^2/\omega^2}{\sqrt{\xi/(1+q)}}\right)$$

This solution for $t > 0$ and $t >> 1$ decreases as $\exp\left(-\frac{2}{3}t^{3/2}\right)$, whereas for $t < 0$ and $|t| >> 1$ it is the wave incident on a resonant layer (helicon or QE mode) and the converted wave (QE mode or helicon) with the amplitude that is equal to that of the incident wave. This means the total conversion of modes with the damping neglected. The solution obtained matches asymptotically the WKB solution.

It follows from the expressions obtained above that for $N_\parallel^2 \sim \varepsilon_e$ and $\omega \sim \omega_{LH}$ the effect of ions is important for a QE mode as well as for a helicon. When the frequency approaches ω_{LH}, the conversion point $r = r_c$ is shifted from the region, where $N_\parallel^2 = 4\varepsilon_e$ for $\omega >> \omega_{LH}$, to the region where $N_\parallel^2 = \varepsilon_e$ with $\omega = \omega_{LH}$.

The formulas obtained above are reduced to those obtained in paper [8] for $N_\parallel^2 >> \varepsilon_e$ and $q << 1$. (Note the misprints: in formula (1) of paper [8] one should change the minus sign before the term $2i\nu/\omega$ for plus one; one should also omit the factor 2 in the term of formula (3) proportional to $i\nu/\omega$.)

3. We have calculated the electric and magnetic fields and the profile of the RF power $P(r)$ absorbed with $\omega \sim \omega_{LH}$ for the plasma with the density $n(r) = n(0)\cdot\left(1 - r^2/a^2\right) + n(a)\,r^2/a^2$ and the mode $m = 1$ with the density of the external current $j_0 = \left(j_\phi^2 + j_z^2\right)^{1/2}$=100 A/cm. Below we give the graphs of the radial component E_r exceeding E_ϕ and E_z considerably.

The E_r and $P(r)$ profiles at $\omega \approx \omega_{LH} \approx \sqrt{\omega_{Ce}\omega_{Ci}}$ for the plasma with the small radius are given for a moderate

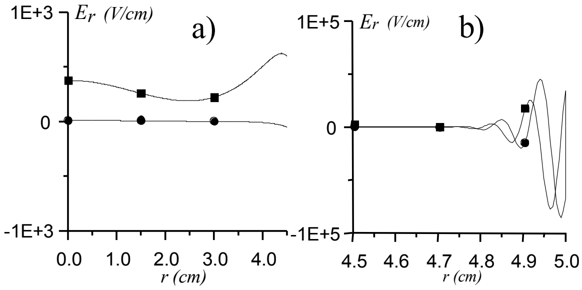

Fig. 1. The E_r radial profile in the regions where a helicon is generated a) and where a surface mode exists b) (the square is for a real part of E_r, and the circle is for an imaginary part of E_r). Calculation parameters: operating gas – argon, $a = 5$ cm, $n_0(0) = 10^{13}$ cm^{-3}, $n_0(a) = 10^{11}$ cm^{-3}, $B_0 = 10^3$ G, $f = 1.12\cdot10^7$ Hz, $T_e = 8\,eV$, $k_z = 0.15$ cm^{-1}, $\nu_{en} = 10^7$ s^{-1}.

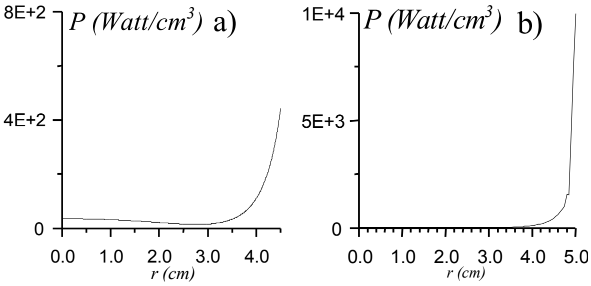

Fig. 2. Radial profile of the specific absorbed power a) in the region where a helicon is generated, b) in the region where a QE mode is generated. Calculation parameters are the same as in fig. 1.

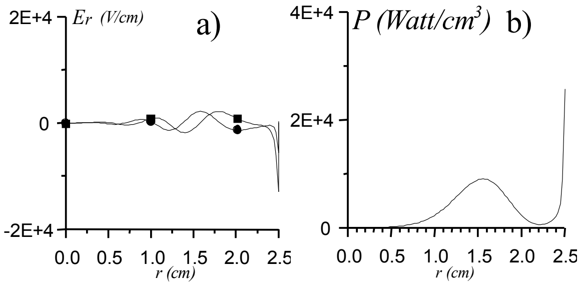

Fig. 3. Radial profiles of E_r a) and the specific absorbed power b). Calculation parameters: operating gas – hydrogen, $a = 2.5$ cm, $n_0(0) = 3\cdot10^{13}$ cm^{-3}, $n_0(a) = 3\cdot10^{12}$ cm^{-3}, $B_0 = 450$ G, $f = 27.12\cdot10^6$ Hz, $T_e = 10$ eV, $k_z = 0.2$ cm^{-1}, $\nu_{en} = 10^7$ s^{-1}.

density and strong magnetic field at $N_\parallel^2/\varepsilon_e(0) \approx 40$ in figs. 1 and 2, and for a large density and a moderate magnetic field, $N_\parallel^2/\varepsilon_e(0) \approx 0.77$ in fig. 3. For a plasma with large radius with $N_\parallel^2/\varepsilon_e(0) = 1$ at $\omega = \sqrt{\omega_{Ce}\omega_{Ci}}$ the excitation of waves and their absorption are depicted in figs. 4 and 5. This case at $N_\parallel^2 >> \varepsilon_e$ was studied in paper [8]. Note that $P(r)$ values in [8] are obtained under the condition that for the discharge with $L_\parallel = 2\pi/k_\parallel$ the absorbed power is equal to 100 W.

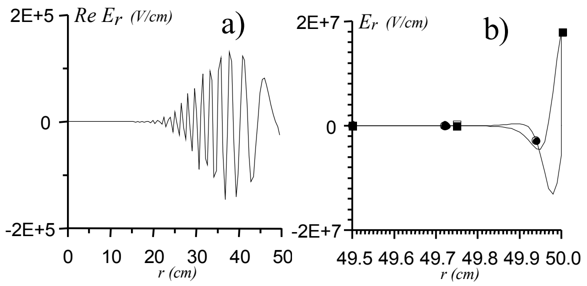

Fig. 4. Radial profile of E_r in the region where a helicon is generated a) and in the region where a QE-mode exists b). Calculation parameters: operating gas – hydrogen, $a = 50$ cm, $n_0(0) = 8 \cdot 10^{12}$ cm^{-3}, $n_0(a) = 10^{11}$ cm^{-3}, $T_e = 10$ eV, $B_0 = 450$ G, $f = 27.12 \cdot 10^6$ Hz, $k_z = 0.13$ cm^{-1}, $\nu_{en} = 5 \cdot 10^6$ s^{-1}.

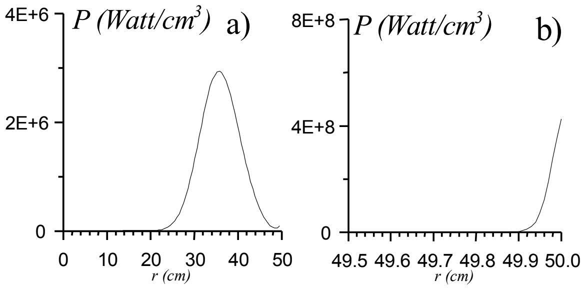

Fig. 5. Profile of the RF power absorbed in the region where a helicon is generated a) and in the regions where a QE-mode exists b). Calculation parameters are the same as in fig. 4.

In all cases the QE mode is localized in a very narrow layer at the plasma edge where it is absorbed completely. The helicon is generated in the bulk plasma and is coupled with the QE mode for $a = 2.5$ cm (fig. 3a) and for $a = 50$ cm. It is totally absorbed not reaching the center. The surface absorption exceeds the volume one considerably for $a = 5$ cm, it is two times less the volume one for $a = 2.5$ cm and is equal to the volume one for $a = 50$ cm.

For the typical values of the RF power absorbed in the discharge of small radius and length $L_{\|} = 100$ cm order of $W = 1.5$ kW the values E_r in figs. 1 and 3 must be diminished 30 and 60 times, respectively, and for the discharge with $a = 50$ cm and $L_{\|} = 50$ cm with $W = 10$ kW E_r in fig. 4 should be diminished $6 \cdot 10^3$ times. In this case the electron drift velocity $v_\phi = cE_r/B_0$ in the helicon field E_r will exceed the ion sound velocity v_s several times, and at the plasma edge in the field of the QE mode, it will approach and even exceed the electron thermal velocity.

The estimate given shows that in the models of helicon sources under consideration the drift velocity $v_\phi > v_s$. As was shown in paper [9], at $\omega \sim \sqrt{\omega_{Ce}\omega_{Ci}}$ the ion-sound parametric instability with $k_\perp \rho_e \sim 1$, where $\rho_e = v_{Te}/\omega_{Ce}$ is the electron Larmor radius, possesses the growth rate considerably exceeding one at $\omega >> \sqrt{\omega_{Ce}\omega_{Ci}}$. Therefore, it is natural to expect that the rate of turbulent heating electrons and ions will exceed that at $\omega >> \sqrt{\omega_{Ce}\omega_{Ci}}$ [10]. This furnishes the possible explanation of the experimental results [6,7].

4. The results outlined above permit one to draw the following conclusions:

a) at $\omega \sim \sqrt{\omega_{Ce}\omega_{Ci}}$ the effect of ions on the dispersion and absorption of the QE mode at the plasma edge is always essential, whereas it is unimportant for the helicon at $N_{\|}^2 >> \varepsilon_e$. If, however, $N_{\|}^2 \sim \varepsilon_e$, then this effect is important for both modes, leading, in particular, to the shift of the conversion radius;

b) for existing values of the RF power introduced, the pumping field, especially in the surface layer, gives rise to nonlinear (parametric) phenomena, specifically, at $\omega \sim \omega_{LH}$ the ion-sound instability is stronger than at $\omega >> \omega_{LH}$, that may give rise to an enhanced anomalous heating of electrons and ions.

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