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Conversion of helicon and quasi-electrostatic modes in nonuniform plasma

. . Kurov, V.V. Olshansky, K.N. Stepanov

National Science Center "Kharkov Institute of Physics and Technology"
1, Akademicheskaya Str., 61108, Kharkov, Ukraine

1. Much of research was devoted to explaining the high performance efficiency of helicon plasma sources as being due to the linear coupling between long-wavelength electromagnetic modes (helicons) and the short-wavelength quasi-electrostatic waves (TG-modes) near the plasma surface [1-6]. The volume linear coupling between these modes is also possible [1], but for long-wavelength oscillations, $|k_r| a \sim 1$ (a is the plasma radius, k_r is the radial wavenumber) it is ineffective [1]. For $|k_r| a >> 1$ at $r \approx r_c$, where $N_{\|}^2 = k_{\|}^2 c^2 / \omega^2 = 4\varepsilon_1(r_c)$, $\varepsilon_1(r) = \omega_p^2(r)/\omega_c^2$ and where with $r = r_c$ the radial wave number k_r of the helicon and the TG-mode coincide, the complete conversion is possible [1]. The present report considers the excitation, propagation, conversion and absorption of such coupled modes in a nonuniform plasma cylinder for $|k_r| a >> 1$. It is shown that the contribution of the surface conversion into the absorption may happen to be small, if electron density at the edge of plasma is small. If the electron velocity oscillations in the electric field of such coupled oscillations exceeds the ion sound velocity, then the kinetic ion-sound parametric instability can be responsible for electron heating, discharge sustainment and absorption of these modes [7]. Similar instabilities have been discovered recently in experiment [8,9].

2. Consider the wave excitation by an external current located on the surface of radius $r_A > a$ outside the plasma cylinder with the electron density $n_0(r)$ immersed in the axial magnetic field $\mathbf{B}_0$, the current density being $\mathbf{j}(r,\varphi,z) = \mathrm{Re}\{(j_\varphi \mathbf{e}_\varphi + j_z \mathbf{e}_z)\cdot \exp[i(m\varphi + k_{\|} z - \omega t)]\ \delta(r - r_A)\}$, where $(m/r_A) j_\varphi + k_{\|} j_z = 0$. We seek the solution to Maxwell's equations in the form $\{\mathbf{E}(r), \mathbf{B}(r)\}\exp[i(m\varphi + k_{\|} z - \omega t)]$. The conditions $\omega_p^2 >> \omega_c^2 >> \omega^2 >> \omega_{LH}^2 = \omega_c^2 (m_e/m_i)$ is assumed to be satisfied, the angle between $\mathbf{k}$ and $\mathbf{B}_0$ is close to $\pi/2$, $\cos\theta = k_{\|}/k << 1$. Than we obtain from the dispersion equation that $k_r^2 = k_\pm^2 >> (m/a)^2$, where

$$k_r^2 = k_c^2 \left\{ N_{\|}^2/(2\varepsilon_1) - 1 - i(\nu/\omega)\cdot (N_{\|}^2/\varepsilon_1 - 1) \pm \sqrt{[N_{\|}^2/(2\varepsilon_1) - 1 - i(\nu/\omega)(N_{\|}^2/\varepsilon_1 - 1)]^2 - 1 - 2i(\nu/\omega)} \right\}, \quad (1)$$

where $k_c = \omega_p(r)/c$, $\nu = \nu_{ei} + \nu_{en} << \omega$. This yields under the condition $N_{\|}^2 / 2\varepsilon_1 >> 1$ the wellknown expressions for a TG-mode and a helicon:

$$k_+^2 = k_{||}^2\left(\omega_c^2/\omega^2\right)\cdot\left(1-2i(\nu/\omega)\right),\;\; k_-^2 = k_c^2\cdot\left(\varepsilon_1/N_{||}^2\right)\left[1+2\left(\varepsilon_1/N_{||}^2\right)\cdot\left(1+i\left(\nu/\omega\right)\right)\right]. \quad (2)$$

In this case, $|k_+| >> |k_-|$, the damping $\kappa = \operatorname{Im} k_r$ of the TG-mode is much larger than the helicon damping. At the plasma edge the condition $\omega_p^2 >> \omega_c^2$ can be violated, in this case the quantity k_+^2 from (2) should be multiplied by $\left(1+\omega_c^2/\omega_p^2\right)^{-1}$. At the conversion point

$$k_r^2 = k_c^2\left(1 \pm 2\sqrt{(r_c - r)/a_c - 2i\left(\nu/\omega\right)}\right), \qquad (r \approx r_c) \quad (3)$$

where $1/a_c = (1/n_0)dn_0(r)/dr\,|_{r=r_c}$. Hence it is clear that for $r < r_c$, $a_c < 0$ and small ν/ω the waves are damped according to the exponential law oscillating with the wave vector k_c.

To the damping due to the friction force and determined by the formula (1), one must add the damping due to the transverse electron viscosity (gyrorelaxation effect due to electrons), which contributes to the component of the dielectric permittivity $\varepsilon_{22} = \varepsilon_1 + i\,\delta\varepsilon_{22}$, where $\delta\varepsilon_{22} = \left(2+\sqrt{2}\right)\left(\nu_{ei}k^2 v_{Te}^2\omega_p^2\right)/\left(5\omega^3\omega_c^2\right)$. In this case in the formula (1) an term $\delta\varepsilon_{22}\,\omega^2/2\omega_p^2$ must be added to the quantity $(\nu/\omega)\cdot\left(N_{||}^2/\varepsilon_1 - 1\right)$, and an term $\delta\varepsilon_{22}\left(\omega^2/2\omega_p^2\right)\cdot\;\cdot\left(N_{||}^2/\varepsilon_1 - 1\right)$ must be added to the quantity $2(\nu/\omega)$. The contribution of the electron viscosity may be important only to the helicon damping at $N_{||}^2 >> \varepsilon_1$ for $\beta \sim \omega/(\omega_c\cos\theta)$. In this case in the formula (2) the term $\left(2+\sqrt{2}\right)\cdot\left(\nu_{ei}/\omega\right)\cdot(\beta/5)$, where $\beta = 4\pi n_0 T_e/B_0^2$, must be added to the quantity $2\left(\varepsilon_1/N_{||}^2\right)\cdot(\nu/\omega)$.

Expression (1) can be used for $|k_r|a >> 1$ for the WKB-solution of Maxwell's equations. This approximation is valid when $k_c\cdot\left|(r_c - r)/a\right|^{3/2} >> 1$. For $r \approx r_c >> 1/k_c$ the solution can be expressed through Airy's function ([cf. [10]) $E_\varphi = C_\pm \exp\left[\pm i\,k_c\left(r - r_c\right)\right]$ $Ai(t)$, where $t = \sqrt[3]{k_c^2(-1/a)}\,(r_c - r)$. These expressions present for $(-t) >> 1$ incident wave helicon (or TG mode) traveling to the cylinder axis with $k_r = \mp|k_\mp|$ and converted TG-mode (or helicon) with $k_r = \mp|k_\pm|$ also traveling to (or off) the cylinder axis with the phase velocity $\omega/|k_\pm|$ and with the group velocity directed off the cylinder axis, and having the amplitude that is equal to that of the incident wave with damping neglected. This solution is asymptotically linked to the WKB-solution obtained.

Behavior of the amplitudes of WKB solutions versus radius due to their dependency from density and cumulative effect can be obtained taking into account that average value of

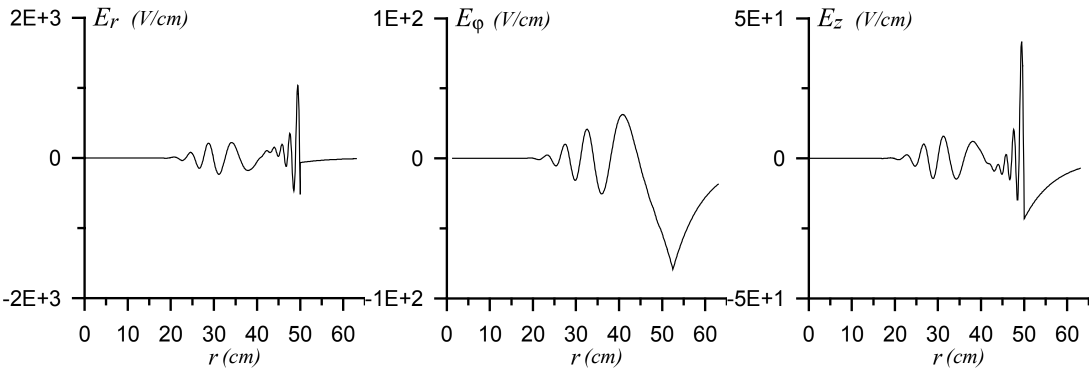

Fig. 1.RF field radial profile ($n(0)$=1.4·10^{12} cm^{-3}, $n(a)$=2·10^{10} cm^{-3}, p ~10mTorr).

radial flux of RF power is constant, if damping is small.

3. Consider the results of the numerical solution of Maxwell's equations with $n(r) = n_0\left[1-\alpha\left(r^2/a^2\right)\right]$, T_e=4 eV, a=50 cm, B_0=300 G, $m = 0$, $k_{||} = 0.13$ cm^{-1}, $\omega/2\pi$ =28.66 Hz, r_A=52.5 cm, $j_\varphi = 100\, A/cm$, operating gas being argon.

Fig. 1 depicts the radial profiles of the real parts of amplitudes for the plasma with the high neutral gas pressure ($\nu_{en} \approx 2\cdot 10^7$ s^{-1} $> \nu_{ei}$), whereas Fig. 2 shows the radial profile of the absorbed RF power density. The dependence of imaginary parts of amplitudes is similar to their real parts. In this case the collisions with neutral particles play an important role. A small-scale TG-mode is excited at the plasma edge with k_r from Eq. (2). Decreasing of $E_{r,z}$ for this mode is linked with increasing of $n_0(r)$ and with their collisional damping. The oscillations of E_φ and B_r are very small and are not visible in Fig. 1, the amplitudes $B_{\varphi,z}$ are small too (~1÷2 G). A large-scale helicon is also excited at the edge and the wave propagates to the plasma centre. Its wavelength decreases. In the region $r_c \approx 25$ cm the helicon is conversed into the TG-mode. The helicon is damped at the edge weakly. The values $E_{r,z}$ and $B_{\varphi,z}$ increase with decreasing of r due to increasing of $n_0(r)/r$, and the values E_φ and B_z are proportional to $\left(n_0(r)\cdot r\right)^{-1/2}$. In the region $\varepsilon_1 \sim N_{||}^2$ and $r \sim r_c$ for $r < r_c$ all amplitudes decrease exponentially. The power is mainly absorbed in the vicinity of the conversion point.

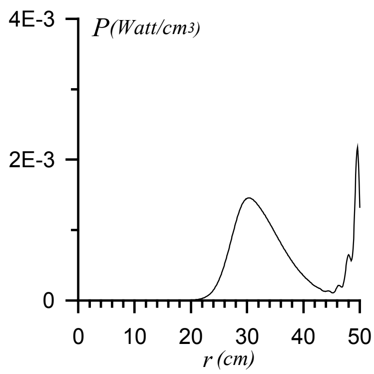

Fig. 2. RF power absorption radial profile. The calculation parameters are identical with those in Fig. 1.

Under small pressure of the operating gas, $p <$ 10^{-5} Torr, we have $\nu_{ei} >> \nu_{en}$ (see

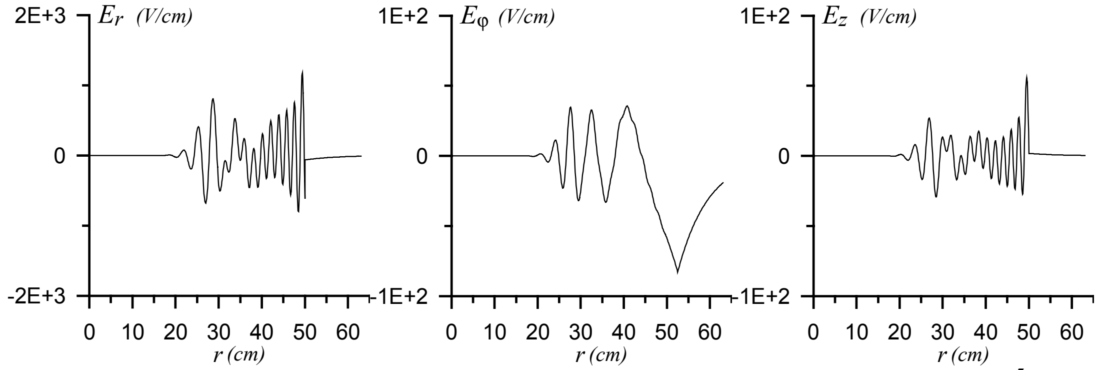

Fig. 3. RF field radial profile under small pressure of the operating gas, $p < 10^{-5}$ Torr. The rest of the calculation parameters are the same as in Fig. 1.

Figs. 3,4). Behavior of the amplitudes versus radius is similar to one depicted in Fig. 1 The region of localization of the surface TG-mode expands. However, the fraction of the surface conversion is less than 30% of the absorbed power. The main fraction of the absorbed RF power is concentrated in the region $r \sim r_c$.

On decreasing $n_0(r)$, the point r_c shifts to the values for 16 cm $n(0) = 1.2 \cdot 10^{12}\ cm^{-3}$. The amplitudes do not practically depend on radius outside the edge. With further decrease of the density, the conversion point disappears. But if the value $n(0)$ is close to the critical one, the increase of $E_{r,\varphi,z}$ and $B_{r,\varphi,z}$ with r decreasing due to cumulative effect becomes important.

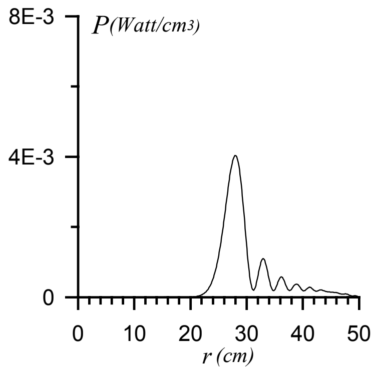

Fig. 4. Radial profile of the absorbed RF power ($p <\ 10^{-5}$ Torr). The calculation parameters are identical to those in Fig. 3.

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