Investigation of the O-mode anomalous absorption in the UH resonance

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High power ECRH is widely used nowadays for heating of electron component, current drive, control of neoclassical tearing modes and is considered for application in ITER. Since 80th nonlinear effects such as parametric decay instabilities (PDIs) were believed to be deeply suppressed in the second harmonic extraordinary mode and first harmonic ordinary mode ECRH experiments in toroidal magnetic fusion devices [1]. Nevertheless, during the last decade a number of anomalous phenomena observations have been reported in second harmonic ECRH experiments [2-4] such as fast ion generation [2, 3] and anomalous backscattering [4]. An explanation of these observations proposed recently is based on possibility of low-threshold parametric excitation of decay waves trapped in plasma due to non-monotonic behaviour of plasma density in radial direction [5, 6] associated with density pump out effect, magnetic islands, drift-wave eddies or blobs and density maximum at the discharge axis. In principle, this mechanism is not specific for the second harmonic ECRH and can occur in the case of first harmonic O-mode heating in contemporary devices and in ITER.

In this report we analyse a possibility of low-threshold parametric excitation by the O-mode pump of the upper hybrid (UH) waves localised in the axially symmetric plasma filament elongated in the magnetic field direction. The theory predictions are compared to the results of model experiments on interaction of ECR frequency range microwave O-mode pump with inhomogeneous plasma performed at the linear plasma device "Granit" [7].

Theoretical approach and results.

We consider the decay of the ordinary pump wave propagating perpendicular to the magnetic field and possessing the electric field given by expression $E_{0z} = \sqrt{\dfrac{8P_0}{\pi ZYc}} \exp\left(-\dfrac{z^2}{2Z^2} - \dfrac{y^2}{2Y^2} - i\omega_0 t\right)$, where z, y are directions along and transverse to the magnetic field respectively and P_0 is the pump wave power. The wave number of the pump wave is supposed to be negligible compared to wave numbers of the decay waves. We use cylindrical coordinate system below with the axial direction along the magnetic field. The basic equations describing generation of UH wave $\varphi_{uh} = \tilde{\varphi}_{uh}(r)\exp\left(ik_z z + im\phi - i\omega t\right)$ and low frequency (LF) daughter wave $\varphi_{lf} = \tilde{\varphi}_{lf}(r)\exp\left(-ik_z z - im\phi - i\Omega t\right)$ are as follows:

$$\left[\left(\varepsilon+\beta\,\Delta_{\perp}\right)\Delta_{\perp}+\eta\frac{\partial^2}{\partial z^2}\right]\varphi_{uh}=-4\pi\rho_{uh} \tag{1}$$

$$\hat{L}\varphi_{lf}=-4\pi\rho_{lf} \tag{2}$$

Here the permittivity tensor components are given by $\varepsilon=1+\delta\varepsilon_e(\omega)$; $\delta\varepsilon_e(\omega)=-\frac{\omega_{pe}{}^2}{\omega^2-\omega_{ce}{}^2}$; $\eta_{uh}=1-\frac{\omega_{pe}^2}{\omega^2}$; $\beta=\frac{\omega_{pe}{}^2 v_{Te}{}^2\left(\omega^2+3\omega_{ce}^2\right)}{\left(\omega^2-\omega_{ce}^2\right)^3}$; $v_{Te}=\sqrt{2T_e/m_e}$; $\Delta_{\perp}=\Delta-\frac{\partial^2}{\partial z^2}$; $\hat{L}$ is the LF wave operator and the nonlinear charge densities are given by $\rho_{uh}=\frac{i}{4\pi}\delta\varepsilon_i(\Omega)\delta\varepsilon_e(\omega)\frac{E_0k_z}{\omega_0^2}\frac{e}{m_e}\Delta\varphi_{lf}^*$; $\rho_{lf}=-\frac{i}{4\pi}\delta\varepsilon_i(\Omega)\delta\varepsilon_e(\omega)\frac{E_0k_z}{\omega_0^2}\frac{e}{m_e}\Delta\varphi_{uh}^*$; $\delta\varepsilon_i(\Omega)=-\frac{\omega_{pi}^2}{\Omega^2}$.

In the absence of the pump wave (1) the WKB representation $\tilde{\varphi}_{uh}=\varphi_0 e^{i\int k_r dr}$ for the UH wave potential results in the following dispersion relation

$$D\left(k_r,r,\omega\right)=\left(\varepsilon(r)+\beta\left(k_r{}^2+\frac{m^2}{r^2}\right)\right)\left(k_r{}^2+\frac{m^2}{r^2}\right)+\eta k_z{}^2=0 \tag{3}$$

In the case of standard plasma density profile possessing maximal value higher than the UHR density at the filament axis this dispersion relation describes UH waves trapped in the plasma. In particular, for the azimuthally propagating waves ($k_r{}^2 \ll \frac{m^2}{r^2}$) the UH wave localization takes place in the vicinity of the point where the following set of equations is satisfied for $k_{rl}=0$: $\left\{D(\omega_l,k_{rl},r_l)=0;\quad \left.\frac{\partial D}{\partial r}\right|_{\omega_l,k_{rl},r_l}=0\right\}$. In the vicinity of this point equation (1) for the potential takes the form

$$\left[\left(\omega-\omega_l\right)D_\omega+\delta k_z D_{k_z}+\frac{\left(r-r_l\right)^2}{2}D_{rr}-\frac{1}{2}D_{k_rk_r}\frac{\partial^2}{\partial r^2}-i\delta D\right]\tilde{\varphi}_{uh}(r)=-4\pi\rho_{uh}e^{-im\phi}e^{-ik_zz} \tag{4}$$

where $\delta D=\frac{\omega_{pe}{}^2}{2\omega_{ce}{}^2}\sqrt{\pi}\frac{m^2}{r_0{}^2}\exp\left(-\frac{\left(\omega-\omega_{ce}\right)^2}{k_z{}^2v_e{}^2}\right)$ stands for electron cyclotron damping. In the absence of the pump and damping we put $\delta k_z=0$ and for $\omega_n=\omega_l-\left(2n+1\right)\frac{\sqrt{D_{k_rk_r}D_{rr}}}{D_\omega}$ obtain the localized solution of equation (4) in the form

$$\tilde{\varphi}_{uh}^{(0)}\left(r,n\right)=\exp\left[-\left(r-r_l\right)^2\sqrt[4]{\frac{D_{rr}}{D_{k_rk_r}}}\right]H_n\left(\left(r-r_l\right)^2\sqrt[4]{\frac{D_{rr}}{D_{k_rk_r}}}\right) \tag{5}$$

where $H_n\left(\zeta\right)$ stands for Hermit polynomial. Assuming the nonlinear interaction and UH wave damping small and accounting for them using the perturbation method we obtain the LF wave amplitude at frequency $\Omega = \omega_0 - \omega$ in the form $\tilde{\varphi}_{lf}(r) = -4\pi \int G(r, r')\rho_{lf}(r')dr'$ where G is the Green function corresponding to the L operator in equation (2). Finally the perturbation of the UH wave's axial wavenumber associated with nonlinear interaction and damping is given in the perturbation theory by

$$\delta k_z^n = \frac{-4\pi \int \tilde{\varphi}_{uh}(r,n)\rho_{uh}(r)dr + i\int \tilde{\varphi}_{uh}(r,n)\delta D(r)dr}{D_{k_z}\int [\tilde{\varphi}_{uh}(r,n)]^2 dr} \qquad (6)$$

where $-4\pi\rho_{uh} = \delta\varepsilon_i(\Omega)\delta\varepsilon_e(\omega)\frac{E_i k_z}{\omega_i^2}\frac{e}{m_e}\Delta\left[\int G(r, r')\delta\varepsilon_i(\Omega)\delta\varepsilon_e(\omega)\frac{E_i k_z}{\omega_i^2}\frac{e}{m_e}\Delta\varphi_{uh}(r,n)\,dr'\right]$. The threshold of convective PDI in this case is determined by condition $\delta k_z Z > 1$. In the case of ion acoustic LF wave the operator L takes a form $\hat{L} = \frac{\omega_{pi}^2}{c_s^2} - \frac{\omega_{pi}^2}{\Omega^2}\Delta$, where $c_s = \sqrt{T_e/m_i}$ allowing explicit calculation of the Green function and determination of the PDI threshold using (6). Theoretically predicted dependence of the threshold power on the UH wave axial wavenumber is shown in Fig.1 for experimental parameters (H=500Oe, n_e=$8\times10^{10}cm^{-3}$, T_e=$1eV$) . This dependence possesses a clear minimum of 10W determined by competition of nonlinear drive and cyclotron damping both growing with increasing wavenumber.

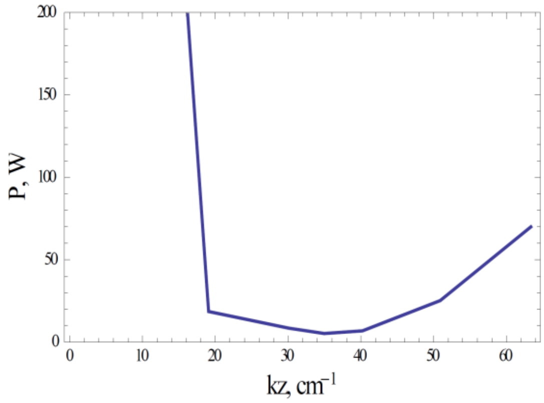

Fig.1. Dependence of the PDI threshold on axial wavenumber of UH wave.

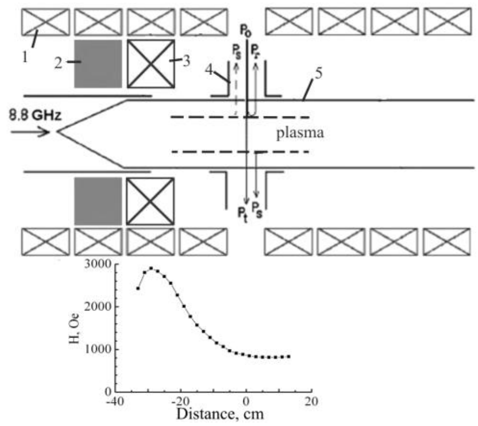

Fig.2. The experimental scheme and the magnetic field distribution. 1 – coils, 2 – iron insertion, 3 – additional coil, 4 – waveguide 72×34 mm^2, 5 – glass tube. P_0, P_t, P_r– incident, transmitted and reflected RF powers.

The experimental observations.

The experiments were carried out on the linear plasma device "Granit" [7] possessing two section with different magnetic field shown in Fig.2. The region at the magnetic system end with high field (~0.3 T) is used for background plasma generation by ECR discharge at frequency 8.8 GHz. In low magnetic field region in the center of magnetic system the plasma volume (2.5 cm in diameter) filled by argon at the pressure of 1 Pa is crossing the waveguide 72 x 34 mm^2 using which the microwave at frequency f_0 = 2.35 GHz and power up to 200W is launched. The microwave electric field is parallel to the external magnetic field. Magnetic field in the waveguide region is homogeneous and variable in the range 450-850Oe. The incident RF absorption in the waveguide was characterized using plasma light radiation intensity as well as transmitted and reflected RF power variation. The absorption dynamics for the microwave pulses (8 μs) at frequency f_0=2.35 GHz was investigated at power up to 200 W for magnetic field variation in the range of 450-850Oe. It is shown, that at small electron densities ($n_e \sim 10^9$ cm^{-3}) absorption takes place only in plasma in narrow range of magnetic field – 750-830 Oe corresponding to ECR (see Fig.3). The additional absorption range steadily grows at higher electron densities. At the volume averaged density $n_e \sim 5\times10^{10}$ cm^{-3} the maximal absorption is observed at much lower magnetic field (~550Oe), as it is seen in Fig.4. This effect could be related both with the PDI excitation and the two-dimensional hybrid resonance phenomena. To exclude the latter possibility the radiation intensity dependences on the pump power at different magnetic fields was investigated. As it is seen in Fig.5, in the high magnetic field case the dependence is linear crossing the origin, which is typical for linear ECR absorption. On contrary, in the low-field case a threshold-like dependence is observed, crossing the power axis at P= 20 – 30W and indicating the possibility of anomalous absorption. The experimental threshold value is close to the theory prediction for localized UH wave parametric excitation.

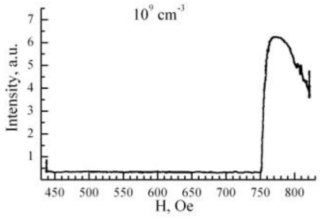

Fig.3. Dependence of additional radiation on magnetic field at low plasma density.

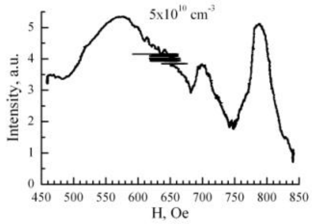

Fig.4. Dependence of additional radiation on magnetic field at high plasma density.

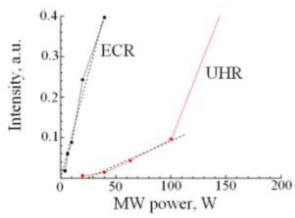

Fig.5. Dependence of additional radiation on the pump power for different magnetic fields.

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