The microwave anomalous absorption in plasma due to the two-upper-hybrid-plasmon parametric decay instability

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1. Introduction

Over the last decade a substantial number of observations accumulated in the ECRH experiments in toroidal devices appeared not fitting into a paradigm that they are adequately described in the linear approximation for the microwave propagation and absorption. The most eloquent one among them is the pump mm-wave anomalous backscattering studied in detail in the X2 ECRH experiments at TEXTOR [1]. The radiation temperature of the observed frequency downshifted backscattering signal was shown to be thousand times larger than the electron temperature, whereas the amplitude of the signal appeared to be modulated at the magnetic island rotation frequency. The most intensive anomalous backscattering was observed at the plasma density in the magnetic island coinciding with the upper hybrid density for the frequency equal to the half value of the pump frequency. In order to explain the latter observation the theoretical model [2] was proposed recently. It interprets the anomalous backscattering as a consequence of the two-upper-hybrid (UH)-plasmon parametric decay of the pump wave possessing very low threshold due to the daughter UH waves trapping in a direction of the plasma inhomogeneity in the vicinity of a local maximum of the density profile often observed in the magnetic island. The theoretical model also predicts substantial (up to 25%) anomalous absorption of the pump power. This makes important further investigation of the mechanism of excitation and the scenarios of the saturation of low-power-threshold two-plasmon parametric decay instability (PDI) of mm-wave.

In order to study this phenomenon in detail the model experiment has been performed at the linear device. The decay occurs in a plasma filament extended in the direction of the magnetic field and produced by a high-frequency discharge in a long quartz tube with its inner diameter of d =22 mm filled with argon at about 1 Pa pressure. The quartz tube passes through the waveguide (72 x 34 mm2) in parallel to the wide wall. The RF power of about 100 W at frequency of 27 MHz is supplied to the ring electrodes placed outside of the tube and disposed on both sides of the waveguide at a distance of 30 cm. At the maximal RF power the volume averaged plasma density measured using the cavity diagnostics is about 10^{10} см$^{-3}$ varying by 15-20% at the variation of the magnetic field from от 0 до 450 Gs. The radial distribution of the plasma luminosity is approximated by expression $(1-r^2/(d/2)^2)^2$. Assuming it to be proportional to the plasma density we get the maximal density in the discharge to be about 1×10^{10} см$^{-3}$. The X-mode microwave pulses (up to 200 W) were incident onto the plasma along the waveguide. As the frequency of the launched waves f_0 = 2.35 GHz is much bigger than the upper hybrid (UH) and electron cyclotron resonance (ECR) frequencies in the plasma volume, it seems that there were no any linear mechanisms of the wave-particle interaction. The temporal behaviour of the transmitted and reflected microwave signal as well as the plasma luminosity was monitored in the experiment at the different pump power and magnetic field. The low-frequency plasma turbulence was investigated using the UHR enhanced microwave scattering diagnostics at frequency of about 1.2 GHz.

2. Theoretical model

In order to describe features of the model experiment on the linear device "Granit" we have to refine the theoretical model [2] which predicts the excitation of low-threshold two-plasmon decay of the pump wave and allows describing the fine details of the frequency spectrum of the anomalously reflected signal and its absolute value in the X2 ECRH experiments at TEXTOR. We start with consideration of the pump signal. In a rectangular waveguide the electric field of the dominant mode $TE_{1,0}$ is determined as follows $\mathbf{E} = \mathbf{e}_y E_0(z)\exp(ik_x x - i\omega_0 t) + c.c.$ where x and z are the Cartesian

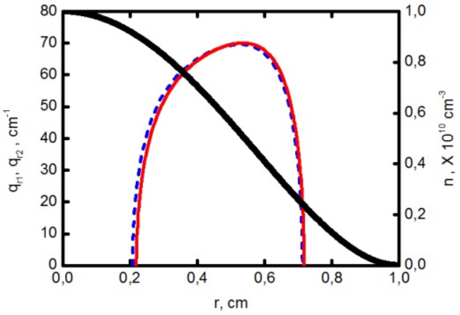

Figure 1. (left and bottom axes) – Dispersion curves of the UH waves q_{2r} ($f_2 = 1.177$GHz, $s = 15$, dashed line) and q_{1r} ($f_1 = f_0 - f_2$, s+1, solid line); (right and bottom axes) – density profile (thick solid line); $H = 320$Gs , $T_e = 2$eV .

coordinates along the waveguide axis and the magnetic field, respectively, and *y* is the coordinate perpendicular to both of them. We have also introduced new notations, namely, $E_0(P_0,z) \propto \cos(\pi z/(2w_z))$, P_0 is the pump power, $k_x = \sqrt{\omega_0^2/c^2 - \pi^2/w_z^2}$, ω_0 is the pump frequency and *c.c.* is the term derived from the first one by complex conjugation. As for the experimental conditions the vacuum wavelength of microwave radiation transmitted through the waveguide $2\pi/k_x$ is much bigger than the tube diameter, one can ignore the spatial structure of the wave in the plasma and put $k_x = 0$. For description of the plasma in the quartz tube it is quite natural to introduce a cylindrical coordinate system (ρ,θ,z) with its origin resting on the tube axis and the coordinate *z* projecting along it. In this coordinates the electric field of the pump wave propagating across the magnetic field is represented by expression

$$\mathbf{E} = E_0(z)(\mathbf{e}_\theta \cos\theta + \mathbf{e}_r \sin\theta)\exp(-i\omega_0 t)/2 + c.c. \qquad (1)$$

where θ is the azimuthal angle. Then, we consider the pump wave's decay into a couple of the electrostatic UH waves propagating in opposite directions and represented by the potentials

$$\phi_1(\mathbf{r},t) = b_{s+1}(z,t)\varphi_{n_1,s+1}(\rho)\exp(i(s+1)\theta + iq_z z - i\omega_1 t), \phi_2(\mathbf{r},t) = b_s(z,t)\varphi_{n_2,s}(\rho)\exp(is\theta + iq_z z + i\omega_2 t) \quad (2)$$

Equation (2) describes the radially trapped and azimuthally propagating UH waves, satisfying the decay condition $\omega_2 = \omega_0 - \omega_1$ and possessing the high azimuthal eigennumbers s+1, s >> 1. The eigenfunctions $\varphi_{n,m}$ ($n = n_1, n_2$, $m = s+1, s$) in the WKB approximation are represented as follows $\varphi_{n,m}(\rho) = \cos\left(i\int_{r_{1,2l}}^{\rho} q_r(\xi,m)d\xi - i\pi/4\right)/\sqrt{q_r(\rho,m)}$ where

$$q_r = \sqrt{-\varepsilon/(2l_T^2) - \sqrt{\varepsilon^2 + 4l_T^2\left(\eta q_z^2 + g^2\omega^2/c^2\right)}/(2l_T^2) - m^2/r^2} \qquad (3)$$

is the radial component of the UH wave wavenumber, ε, g, η are the components of the "cold" dielectric tensor and $l_T^2 = 3\omega_{pe}^2\upsilon_{te}^2/(2(\omega^2 - 4\omega_{ce}^2)(\omega^2 - \omega_{ce}^2))$. The frequencies and parallel wavenumbers of the interacting UH waves obey the quantization conditions, *i.e.* $\int_{r_{1l}}^{r_{1r}} q_r(\xi,\omega_1^{n_1,n_2},q_z^{n_1,n_2})d\xi = \pi(n_1 + 1/2)$, $\int_{r_{2l}}^{r_{2r}} q_r(\xi,\omega_0 - \omega_1^{n_1,n_2},q_z^{n_1,n_2})d\xi = \pi(n_2 + 1/2)$ with $(r_{1,2l}, r_{1,2r})$ being the waves turning points in the radial direction. The dispersion curves (3) indicating the UH wave localization region are shown in figure 1 for the typical conditions of discharge on the linear device «Granit» along with the plasma density profile.

In weakly inhomogeneous plasma a set of equations describing the amplitudes of the nonlinear coupled UH waves (2) both trapped in the radial direction and running in opposite directions along the azimuthal angle reads as

$$\left(\frac{\partial}{\partial t} + u_{1z}\frac{\partial}{\partial z} + \nu_d\right)b_1 = i\frac{E_0}{4H}\Gamma_{12}(z)b_2, \; \left(\frac{\partial}{\partial t} - u_{2z}\frac{\partial}{\partial z} + \nu_d\right)b_2 = -i\frac{E_0^*}{4H}\Gamma_{21}b_1 \qquad (4)$$

where u_{1z} and u_{2z} are the group velocities averaged over the UH plasmons radial localization areas and describing their convective energy losses along the axis $\mathbf{e}_z$; $\nu_{d1,2}$ are the averaged coefficients describing the electron-atom collisional damping; $\Gamma_{12,21} = \gamma_0 / \int_{r_{1,2l}}^{r_{1,2r}} (s/\rho)^2 d\rho / |q_{r1,2}|$ with

$$\gamma_0 = c\left[\frac{\omega_{ce}}{4}\left[\frac{1}{\omega_0} + \frac{s+1}{\omega_1} - \frac{s}{\omega_2}\right] + \frac{\omega_{ce}^2}{\omega_0^2}\right]\int_{\max(r_{1l},r_{2l})}^{\min(r_{1r},r_{2r})}\frac{d\rho}{\sqrt{|q_{r1}||q_{r2}|}}\frac{s^2}{\rho^3}\exp\left(i\int^{\rho}(q_{r1} - q_{r2})d\rho'\right) \qquad (5)$$

are coefficients describing the nonlinear coupling of the UH wave in the presence of the pump wave. It should be noted that for the experimental conditions of the linear device "Granit" the collisional damping rate $\nu_{d1,2} = f(\nu_{ea}) \propto 3 \div 5\mu s^{-1}$ exceeds substantially the daughter wave convective loss rate throughout the decay layer along the magnetic field $\tau_c^{-1} = u_{1,2z} / w_z \propto 10^{-2} \mu s^{-1}$. Under these conditions we may neglect the convective losses in our analysis and obtain the following expression for the absolute PDI growth rate

$$2\gamma_s = -(\nu_{d1} + \nu_{d2}) + \sqrt{(\nu_{d1} + \nu_{d2})^2 + 4\Gamma_{s,s+1}\Gamma_{s+1,s} - 4\nu_{d1}\nu_{d2}} \quad (6)$$

This expression at $\gamma_s = 0$ is providing the PDI threshold, which is determined by the plasmon collisional damping according to the formula $\Gamma_{s,s+1}\Gamma_{s+1,s} = \nu_{d1}\nu_{d2}$ similar to the corresponding threshold in homogeneous plasma theory.

Most likely, the saturation of two-plasmon PDI occurs due to a spontaneous parametric decay of the primary daughter UH waves leading to excitation of the frequency down-shifted UH waves trapped in the magnetic island and the ion acoustic waves. This mechanism will be analyzed analytically in the forthcoming paper in the way similar to the one utilized in [2].

3. Experimental results

At small plasma density no any distortion of the microwave pulse transmitted through the plasma or reflected from it was observed during the pulse duration, as it is seen in figure 2a. However at plasma density exceeding a large enough critical value after a time delay dependent on the power value, a very fast decrease of both transmitted and reflected power was observed thus indicating the turning on of the anomalous absorption (see figure 2b). This effect was accompanied by a sharp growth of the plasma luminosity also shown in this figure. The critical density needed for switching on of the anomalous phenomena grows when the magnetic field decreases, as it is shown by circles in figure 3. As it is seen there, this dependence is close to the theoretical UHR density dependence on the magnetic field plotted in the figure for half the pump frequency that indicates the relation of the observed phenomena to the excitation of two-UH-plasmon decay. The time delay of the anomalous phenomena appearance was dependent on the pump power, as it is seen in figures 2b and 2c, however its main features look similar. Starting from the very beginning of the microwave pulse a slow decrease of the reflected power is accompanied by a slow increase of the plasma luminosity, whereas the transmitted power is constant. Then, an abrupt decrease of the transmitted power happens, which is followed by a very fast fall of the reflected power and growth of the plasma luminosity. Later on the reflected power increases, however not reaching the value it has before the onset of the anomalous absorption. The temporal delay of the anomalous absorption onset is most likely associated with the time needed for growth of the UH wave noise from the thermal level to the PDI saturation level. In order to check this hypothesis we plot the dependences of inverse delay time against the pump power measured at the constant plasma density and magnetic field and compare them to the expression (6), *i.e.* $1/T = \gamma_p / \ln(b_m / b_{th})$, provided by the theoretical analysis with b_m / b_{th} being a rate of increase of the UH waves amplitudes from the thermal noise level to the saturation. As it is seen in figure 4, the experimental data fits the theoretical dependence of the PDI growth rate on the pump power at an assumption of the UH noise amplification in saturation regime by 10 orders of magnitude.

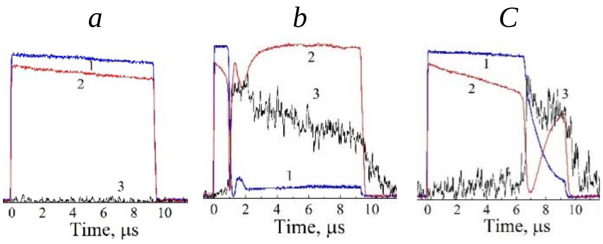

Figure 2. Waveforms of transmitted (1) and reflected (2) pulses and of the plasma luminosity (3). a –small plasma density, b – P_0 = 200 W, c – P_0 =70 W.

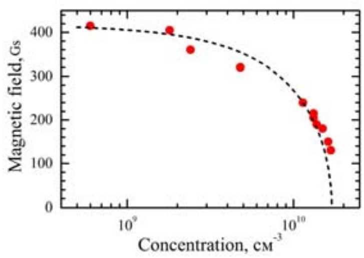

Figure 3. Dependence of the density critical for onset of the anomalous absorption on the magnetic field. Broken line - UHR condition for 1.175 GHz; P_0 = 160 W.

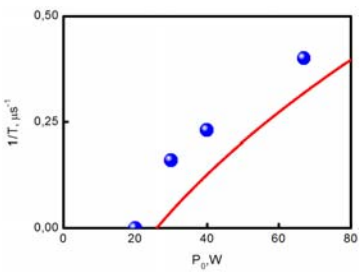

Figure 4. Experimental (stars and circles) and theoretical (dashed line) inverse time of the anomalous absorption onset versus the pump power.

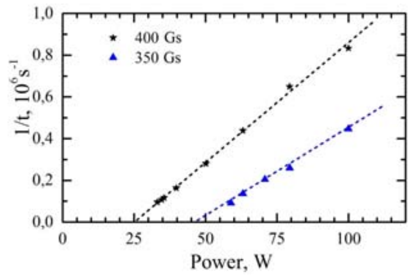

Figure 5. Dependence of the inverse time of the anomalous absorption onset on the pump power for different magnetic fields.

We have also studied the dependence of the two-plasmon instability growth rate on the pump power. The measurements were performed for two magnetic fields 350 and 400 Gs, but at the constant Ar pressure of about 1.5 Pa and volume averaged plasma density of about 10^{10} см^{-3} controlled by the plasma RF source power. The results for the inverse time of the anomalous absorption turning on shown in figure 5 appear to be in a qualitative agreement to the theory predictions for the growth rate increase with increasing pump power and for the PDI power threshold decrease with growing magnetic field.

Thus, we have demonstrated experimentally the excitation of two-plasmon PDI of the pump X-mode wave. We have also shown that the power threshold and the growth rate of the primary instability predicted analytically are in a reasonable agreement with the measured ones.

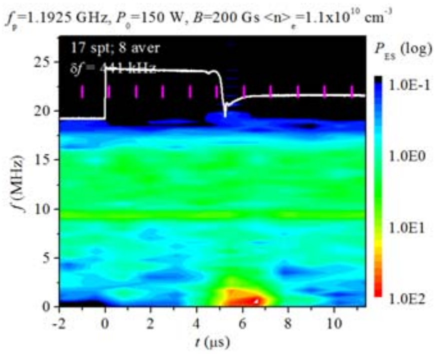

Figure 6. The temporal evolution of the BS spectrum. The upper curve corresponds to the transmitted pulse.

In order to investigate the nonlinear saturation mechanism of the two-plasmon decay instability measurements of the low-frequency small-scale plasma waves were performed using the enhanced UHR backscattering (BS) diagnostics. For this purpose plasma was probed by microwaves in the frequency range 1-1.5 GHz, for which the UHR condition was fulfilled within the plasma volume. It was shown that an intensive BS signal is observed when the probing frequency is close to the half pump frequency. The temporal variation of the BS spectrum is demonstrated in figure 6. The white line on the top of the figure shows the waveform of the transmitted signal. It should be stressed that the most intensive BS signal is observed just in the period of the strongest suppression of the transmitted signal at the pump frequency, thus in the period of the strong anomalous absorption onset. During this period the BS signal is enhanced by two orders of magnitude. The frequency shift of the BS signal is close to 2-3 MHz, which corresponds to the ion acoustic frequency range in line with the PDI saturation mechanism discussed in theory.

5. Conclusions

The strong anomalous absorption of the microwave power is observed in the plasma filament at the density close to the UHR value for the half pump frequency by means of optical and microwave diagnostics. The threshold and growth rate of the anomalous phenomena are shown to agree with the theory results. Its dependence on magnetic field and microwave power are shown to be close to the theoretical predictions for the two-plasmon decay. The low frequency turbulence in the ion acoustic range is shown to be enhanced in the strong absorption onset period.

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References

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