

Observation of the X-mode anomalous absorption in the plasma filament associated with the two upper-hybrid-plasmon decay

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Abstract. The strong anomalous absorption of the X-mode wave associated with the two upper-hybrid-plasmon decay in the plasma at density higher than the UH resonance value for the half frequency of the pump by means of optical and microwave diagnostics is observed. The threshold and growth rate of the anomalous phenomena are estimated and compared to the theory predictions. The low frequency waves excited in plasma are investigated using the enhanced scattering diagnostics.

1 Introduction

In the recent decade there has been accumulated a substantial number of observations in the ECR plasma heating experiments in tokamaks and stellarators that do not fit into a simple linear picture. The most distinct among them are the anomalous backscattering phenomena studied in detail in the second harmonic X-mode heating experiments at the Textor tokamak [1]. In these experiments it was shown that the radiation temperature of the observed frequency downshifted backscattering signal is thousand times larger than the electron temperature, and its amplitude is modulated at the magnetic island rotation frequency. The highest level of anomalous backscattering was achieved when the plasma density in the island coincides with the upper hybrid density for the frequency equal to the half value of the pump frequency. Based on the latter observation the theoretical model [2] was proposed recently allowing to explain the effect of anomalous backscattering as a result of the two upper-hybrid (UH) plasmon parametric decay instability (PDI) possessing very low threshold due to trapping of nonlinearly excited plasmons in the vicinity of the density maximum that accompanies the island. The theory [2] also predicts substantial (up to 25%) anomalous absorption due to this process.

In the present paper the low-threshold two-plasmon PDI leading to excitation of the trapped UH waves is modelled experimentally in the laboratory plasma.

2 Experimental setup

The decay occurs in a plasma filament extended in the direction of the magnetic field and produced by high-frequency discharge in long quartz tube with an inner diameter of 23.5 mm filled with argon at about 2 Pa pressure. Quartz tube passes through the waveguide

(72 x 34 mm²) in parallel to the wide walls (see Fig. 1). The RF power of about 100 W at frequency of 27 MHz is supplied to the ring electrodes placed outside of the

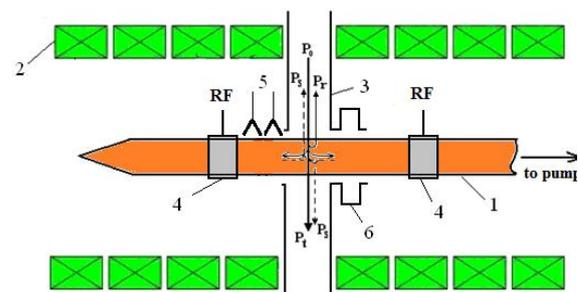


Fig. 1. Schematic of experimental setup. 1 – quartz tube; 2 – magnetic system; 3 – waveguide; 4 – RF antenna; 5 – microwave antenna; 6 – microwave cavity.

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} cm⁻³ changing by 15-20% at the variation of the magnetic field from 0 to 450 Oe. The radial distribution of the plasma luminosity is approximated by expression $(1-r^2)^{1,6}$. Assuming it to be proportional to the plasma density we get the maximal density in the discharge about 2×10^{10} cm⁻³.

The X-mode microwave pulses (up to 160 W) at frequency $f_0 = 2.35$ GHz, substantially higher than the EC and UH values, were incident onto the plasma along the waveguide. The temporal behaviour of the transmitted and reflected microwave signal as well as the plasma luminosity were 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.

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3 Theoretical predictions

The theoretical model of the low-threshold two-plasmon decay proposed in [2] consists of two parts shown schematically in Fig. 2. Firstly, it is a model of the PDI linear stage describing the absolute instability leading to extra-ordinary t_x -wave decay into two UH plasmons $l_{UH}(f_1)$ and $l_{UH}(f_2)$, which are exponentially growing from the thermal noise level b_{therm} . Secondly, it is a model of the absolute instability nonlinear saturation as a result of cascade of several low-threshold decays in which UH waves l_{UH} trapped in plasma and low frequency waves (ion sound l_{IS} in the case of our experiment) are excited. The saturation level b_m determines the efficiency of the anomalous absorption due to the PDI.

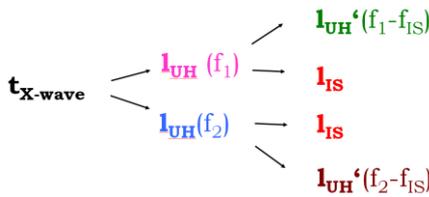


Fig. 2. The scheme of the two-plasmon decay and its saturation.

In the theoretical analysis of the PDI linear stage in the specific ‘‘Granit’’ device conditions we assumed an extraordinary pump wave propagating across the magnetic field and possessing the $m = 1$ mode azimuthal structure represented by expression

$$E_y(\mathbf{r})\mathbf{e}_y = \frac{E_0(z)}{2}(\mathbf{e}_\theta \cos\theta + \mathbf{e}_r \sin\theta)\exp(-i\omega_0 t) + c.c.,$$

$$E_0(z) = \cos\left(\pi \frac{z}{2w_z}\right)$$

where ω_0 – is the pump frequency, z – is the coordinate along the magnetic field and ϑ – is the azimuthal angle.

As a result of the PDI the UH waves are excited and described by their potentials

$$\phi_1(\mathbf{r}, t) = b_{s+1}(z, t)\varphi_{n_1, s+1}(\rho)\exp(i(s+1)\theta - i\omega_1 t), \text{ where}$$

$$\phi_2(\mathbf{r}, t) = b_s(z, t)\varphi_{n_2, s}(\rho)\exp(is\theta + i\omega_2 t)$$

$\varphi_{n_1, s+1}(\rho)\exp(i(s+1)\theta - i\omega_1 t)$ and $\varphi_{n_2, s}(\rho)\exp(is\theta + i\omega_2 t)$ stand for eigen functions describing the radially trapped

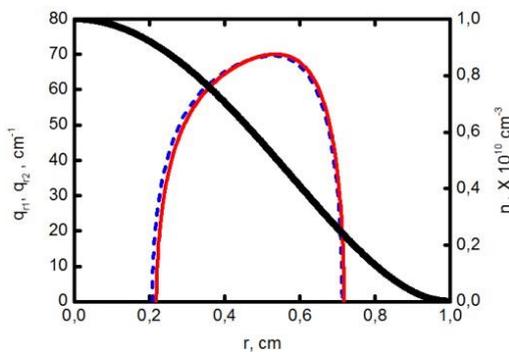


Fig. 3 (left and bottom axes) Dispersion curves of the UH waves q_{r2} ($f_2 = 1.177$ GHz, $s = 15$, dashed line) and q_{r1} ($f_1 = f_0 - f_2$, $s+1$, solid line); (right and bottom axes) – density profile (thick solid line); $H = 320$ Oe, $T_e = 2$ eV.

and azimuthally propagating UH eigen modes satisfying the decay condition $\omega_2 = \omega_0 - \omega_1$, possessing numbers n and s . The dispersion curves (dependence of the WKB radial wavenumber of the UH wave on the coordinate) indicating the UH wave localization region are shown in Fig. 3 as well as the plasma density profile.

The temporal and spatial behavior of the plasmon amplitudes $b_{s+1}(z, t)$ and $b_s(z, t)$ satisfies the following equations taking into account plasmon nonlinear pumping $\Gamma_{s+1, s}$, $\Gamma_{s, s+1}(z)$ collisional damping $\nu_{d1,2}$ and their diffractive losses from the pump localization region:

$$\left(\frac{\partial}{\partial t} + iD_{z, s+1}\frac{\partial^2}{\partial z^2} + \nu_{d1}\right)b_{s+1} = \Gamma_{s+1, s}(z)b_s, \quad (1)$$

$$\left(\frac{\partial}{\partial t} - iD_{z, s}\frac{\partial^2}{\partial z^2} + \nu_{d2}\right)b_s = \Gamma_{s, s+1}(z)b_{s+1}.$$

where at $s \gg 1$

$$\left[\Gamma_{s+1, s}(z); \Gamma_{s, s+1}(z)\right] = \frac{1}{4\pi} \frac{\omega_0 |\omega_{ce}|^2 c}{4\Delta_0} \left[\frac{1}{\omega_0} + \frac{s+1}{\omega_1} - \frac{s}{\omega_2}\right] \times$$

$$\int_{\max(\eta_{1r}, \eta_{2r})}^{\min(\eta_{1r}, \eta_{2r})} \frac{d\rho}{\sqrt{|q_{r1}| |q_{r2}|}} \frac{s^2}{\rho^3} \exp\left(i \int_{\max(\eta_{1r}, \eta_{2r})}^{\rho} (q_{r1} - q_{r2}) d\rho'\right) \times$$

$$\left[\frac{E_0(z)}{H} \int_{\eta_{1r}}^{\eta_{1r}} \frac{dr}{|q_{r1}|} \left(\frac{s}{\rho}\right)^2; \frac{E_0^*(z)}{H} \int_{\eta_{2r}}^{\eta_{2r}} \frac{dr}{|q_{r2}|} \left(\frac{s}{\rho}\right)^2\right]; \text{ and } \Delta_0 = \omega_0^2 - \omega_{ce}^2$$

It should be noted that for the experimental conditions of the ‘‘Granit’’ device the inverse collisional losses time $\nu_{d1,2} = f(\nu_{ea}) \propto 3 \div 5 \mu s^{-1}$ exceeds substantially the diffractive loss time $\tau_D^{-1} = D_{z, s+1} / (\pi w_z^2) \propto 10^{-2} \mu s^{-1}$. Under these conditions we may neglect the diffractive losses in our analysis and obtain the following expression for the absolute PDI growth rate:

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

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.

4 Experimental results and discussion

The first observations of the microwave anomalous absorption at the pump frequency higher than the second electron cyclotron harmonic were performed at the maximal available power of 160 W. The magnetic field was taken smaller than 42 mT, which corresponds to the cyclotron resonance for half the pump frequency of 1.175 GHz. At a small plasma density no distortions of the microwave pulse transmitted through the plasma or reflected from it were observed during the pulse duration, as it is seen in Fig. 4a. However at plasma density exceeding a critical value after a time delay dependent on the density value, a fast decrease of both transmitted and reflected power was observed thus indicating the turning on of the anomalous absorption (see Fig. 4b). This effect was accompanied by a sharp

growth of the plasma luminosity also shown in this figure.

The time delay of the anomalous phenomena appearance was dependent on the pump power, as it is seen in Fig. 4c, however their main features look similar.

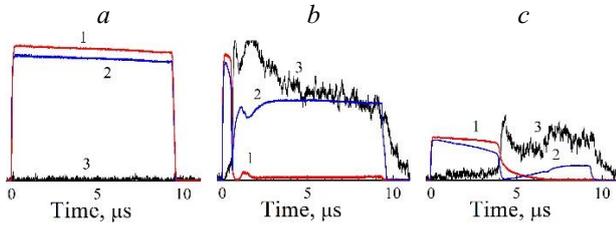


Fig. 4. Waveforms of transmitted (1), reflected (2) pulses and of the plasma luminosity (3). *a* – small plasma density, *b* – $P_0 = 160$ W, *c* – $P_0 = 30$ W

Starting from the microwave beginning a slow decrease of the reflected power is accompanied by a slow increase of the plasma luminosity, whereas the transmitted power is practically constant. Then an abrupt decrease of the transmitted power happens, which is followed by a fast fall of the reflected power and growth of the plasma luminosity. After that the reflected power increases, but doesn't reach the value it had before the onset of the anomalous absorption.

The critical density needed for switching on of the anomalous phenomena is growing with decreasing magnetic field, as it is shown by circles in Fig. 5. As it is

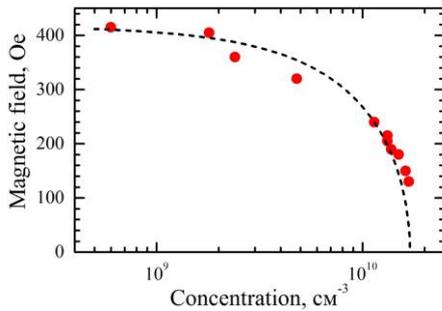


Fig. 5. Dependence of the density critical for onset of the anomalous absorption on the magnetic field. Broken line - UHR condition for 1.175 GHz; $P_0 = 160$ W.

seen there, this dependence is close to the theoretical UHR density dependence on the magnetic field plotted in the figure for the half pump frequency

$$n_e = \frac{m}{4\pi e^2} \left(\pi^2 f^2 - \left(\frac{eB}{m_e c} \right)^2 \right) \quad (3)$$

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 saturation level. In order to check this hypothesis we plotted the dependences of inverse delay time against the magnetic field measured at the constant plasma density, but slightly different pump power and compare them to the expression (2) $\frac{1}{T} = 2\gamma_p / \ln\left(\frac{b_m^2}{b_{therm}^2}\right)$ provided by the

theoretical analysis. As it is seen in Fig. 6 the

experimental data fits the theoretical dependence of the PDI growth rate on the magnetic field at an assumption of of the UH noise amplification in saturation regime by 10 orders of magnitude.

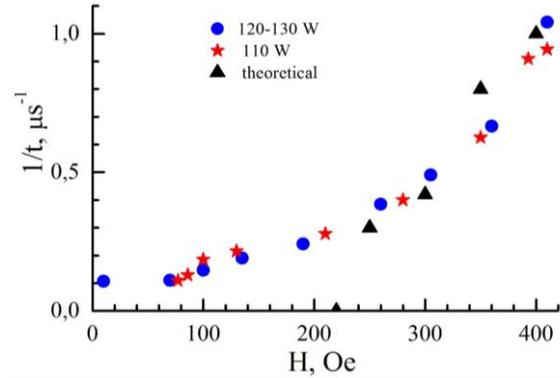


Fig. 6. Experimental (stars and circles) and theoretical (triangles) inverse time of the anomalous absorption onset versus magnetic field.

We have also studied the dependence of the two-plasmon instability growth rate on the pump power. The

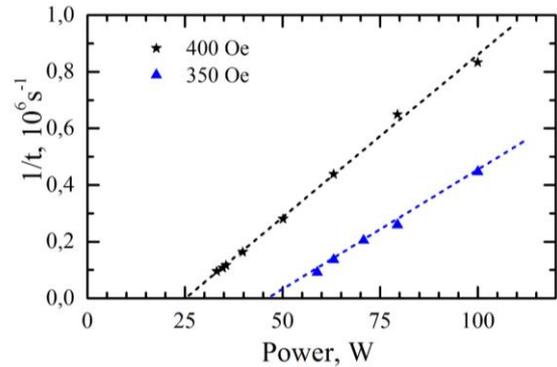


Fig. 7. Dependence of the inverse time of the anomalous absorption onset on the pump power for different magnetic fields.

measurements were performed for two magnetic fields 350 and 400 Oe, but at the constant averaged plasma density about 10^{10} cm^{-3} controlled by the plasma RF source power and Ar pressure of about 1.5 Pa. The results for the inverse time of the anomalous absorption turning on shown in Fig. 7 appear to be in a qualitative agreement to the theory predictions for the growth rate

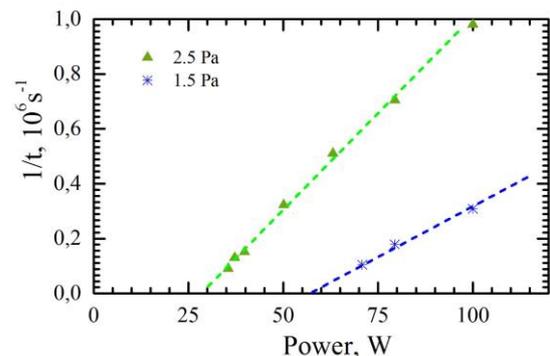


Fig. 8. Dependence of the inverse time of the anomalous absorption onset on the pump power for different values of Ar pressure.

increase with increasing pump power and for the PDI power threshold decrease with growing magnetic field.

The dependence of the inverse time of the anomalous absorption onset on the pump power was also studied for two values of Ar pressure 1.5 Pa and 2.5 Pa. The obtained results shown in Fig. 8 qualitatively confirm the theoretical predictions on the PDI threshold growth with the increasing electron-atom collision frequency and accordingly with the gas pressure.

Using the spatially resolved plasma luminosity measurements we studied the localization of the anomalous absorption, which appeared to be non-central in qualitative agreement with the theoretical expectations based on the UH eigen mode localization (see Fig. 3). Moreover the radial position of the plasma radiation drastic growth determined at the constant value of the averaged plasma volume density was shown to be dependent on the magnetic field. Figure 9 is demonstrating the dependence of the UHR plasma density value, determined using expression (3), values of

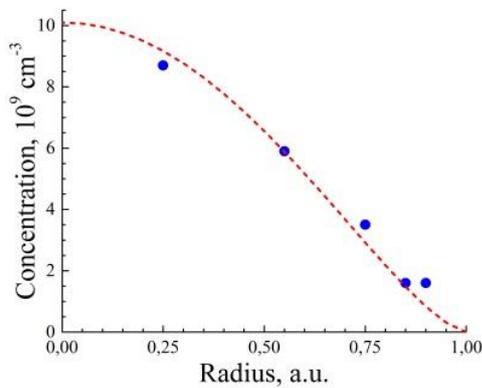


Fig. 9. Dependence of the UHR density value on the radius of the maximal anomalous absorption determined by variation of the magnetic field.

the magnetic field and the half pump frequency, versus the radius of the maximal plasma luminosity growth. As it is seen the obtained dependence fits closely the unperturbed plasma density profile $(1-(r/r_0)^2)^{1.6}$ reconstructed using the volume averaged density measurements and the Abelian transformed profile of plasma luminosity. This agreement, as well as those demonstrated above, confirms the validity of the two-plasmon decay mechanism for explanation of the strong anomalous absorption observed in our experiment.

In order to investigate the nonlinear saturation mechanism of the two-plasmon decay instability, the 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 1.1-1.2 GHz, for which the UHR condition was fulfilled within the plasma volume. It is 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 Fig. 10. 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 only in the period of the strongest suppression of the transmitted signal, thus in the period of the strong anomalous absorption onset. During this period the BS

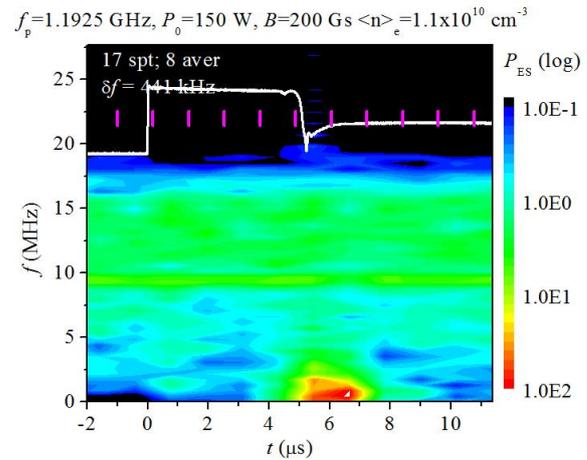


Fig. 10. The temporal evolution of the BS spectrum. The upper curve corresponds to the transmitted pulse.

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 along with the PDI saturation mechanism discussed in theory.

5 Conclusions

The strong anomalous absorption of the microwave power is observed in the plasma at density close to the UHR value for the half pump frequency by means of optical and microwave diagnostics. The effect localization and its dependence on magnetic field, plasma density, gas pressure and microwave power are shown to be close to the theoretical predictions for the two-plasmon decay. The threshold and growth rate of the anomalous phenomena are shown to agree with the theory results. The low frequency waves spectra are shown to be enhanced in the strong absorption period.

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References

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