Experimental investigation of the ordinary wave anomalous absorption in the plasma filament

L. Simonchik[1], A. Altukhov[2], V. Arkhipenko[1], A. Gurchenko[2],

E. Gusakov[2], A. Popov[2], M. Usachonak[1]

[1] *Institute of Physics NAS of Belarus, Minsk, Belarus*

[2] *Ioffe Institute, St-Petersburg, Russia*

1. Introduction

The conventional linear theory fails to explain a number of effects, such as anomalous backscattering and anomalous ion acceleration, observed in experiments on second harmonic X-mode electron-cyclotron resonant heating (ECRH) in toroidal magnetic fusion devices [1, 2]. The theoretical model proposed in [3] explains the anomalous backscattering as a result of the two upper-hybrid (UH) plasmon parametric decay (TUHPD) instability possessing very low threshold due to trapping of excited plasmons in the vicinity of the local density maximum. Model experiments [4, 5] have shown that the anomalous absorption in a plasma filament related to the TUHPD instability can reach 80%. A similar situation, which can occur in the case of ordinary pump wave polarization, is under investigation in the present paper.

2. Experimental setup

The experiment is performed at the linear plasma device where a plasma filament is produced by a RF discharge in a long glass tube with the inner diameter of $2a = 22$ mm oriented in the direction of the magnetic field (Fig. 1*a*) and filled with argon (at pressure about 1.5 Pa). The magnetic field created by the external electromagnet can be varied from 0 to 60 mT. The glass tube passes through the holes made in the wide walls of the waveguide (72×34 mm^2).
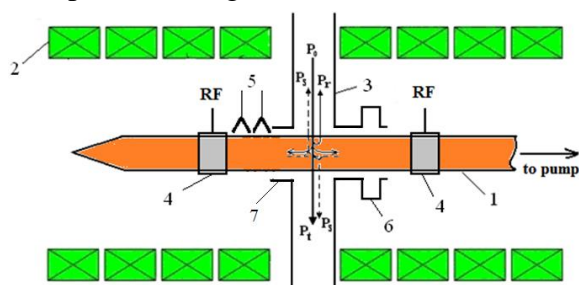

Fig. 1. Schematic of experimental setup: 1 – glass tube a plasma filament, 2 – magnet coils, 3 – weveguide, 4 - electrodes, 5 – antennas, 6 – 10-cm cavity and 7 – belo cutoff waveguide.

The RF power of about 100W 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 about 30 cm. At the maximal RF power (about 100 W) the volume-averaged plasma density measured using the cavity diagnostics situated at a distance of 100 mm from the waveguide axis is about 2×10^{10} cm^{-3}. The radial distribution of integral plasma light emission in the visible spectral region was registered through a slit made in the narrow wall of the waveguide. It can be approximated by the function $(1 - (r/a)^2)^{1.6}$. In the framework of the coronal model applicable to the RF discharge, the electron temperature roughly estimated using the argon lines ratio method is homogeneous within error bars in our case and is in the range of 1-1.5 eV. Assuming the proportionality of light intensity and plasma density we get an upper estimation of the maximal density in this case to be 3-3.5$\times 10^{10}$ cm^{-3}. This value is substantially

smaller than the critical density value 7×10^{10} cm^{-3} providing cutoff for the ordinary pump wave frequency, however it is higher than the critical density for the half pump frequency.

The O-mode microwave pulses (power up to 210 W) are incident onto the plasma along the waveguide. As the frequency of the launched pump wave ($f_0 = 2.35$ GHz) was higher than the upper-hybrid (UH) frequency in the plasma volume, but smaller than the second harmonic of the electron cyclotron resonance (ECR) frequency, there were no effective linear mechanisms of the pump absorption, but the collisional one only, which is weak at the experiment conditions. The temporal behavior of the transmitted and reflected microwave signal as well as the plasma luminosity was monitored in the experiment at different pump power, plasma density and magnetic field.

3. Results and discussion

The experiments are performed at magnetic field induction of $B = 57$ mT. This magnetic field magnitude is higher than electron cyclotron field $B_c = 0.42$ mT for frequency equal a half of pump frequency $f_0 = 2.35$ GHz. The pump pulse duration is about 9 μs, and its shape is close to
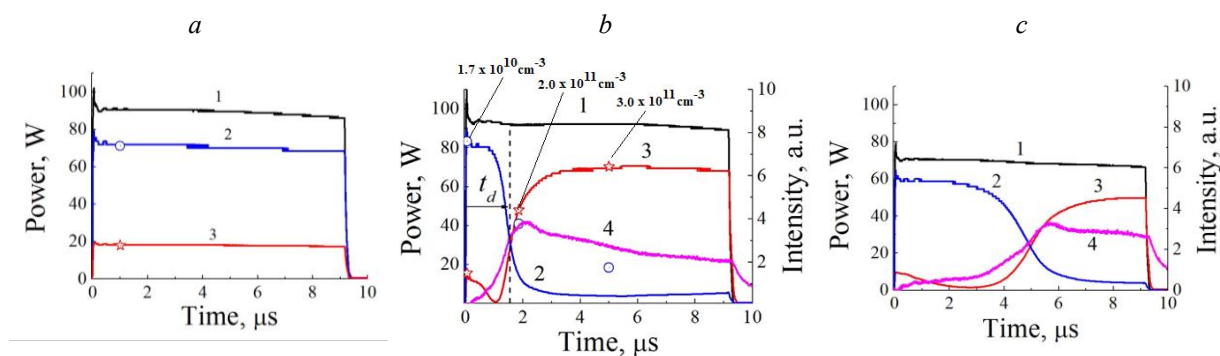

Fig. 2. Waveforms of MW pulses in the waveguide without plasma (*a*) and with plasma at the initial plasma density $n_e \approx 1.7 \times 10^{10}$cm^{-3} for pump power 90 W (*b*) and 70 W (*c*): (1) is incident power P_i, (2) is transmitted P_t, (3) is reflected P_r and (4) is plasma luminosity.

rectangular (Fig. 2*a*, waveform 1). In this experiment, pulse power is about 90 W. At a small plasma density, no distortions of the microwave pulses in waveguide are observed (Fig. 2*a*). The full microwave power balance defined as $P_0 = P_t + P_r + P_h$, where P_0, P_t, P_r, and P_h are powers accordingly incident, transmitted, reflected and a power radiated through holes in waveguide is satisfied. For P_h decreasing, the below cutoff waveguides are used (see Fig. 1). The modelling of wave transmission through the waveguide system was performed using HFSS software [6]. The simulation results are presented in Fig. 2*a* by star and open circle for reflected and transmitted signal, correspondingly. The power P_h seeped through the below cutoff waveguides consists a few percent.

It should be stressed that at plasma density 3-3.5 $\times 10^{10}$ cm^{-3} on the filament axis exceeding a critical value after a time delay dependent on the density value, a fast decrease of both transmitted and reflected power was observed (see Fig. 2*b*). These effects were accompanied by a simultaneous growth of the plasma luminosity (also shown in Fig. 2b, waveform 4) indicating the turning on of the anomalous absorption. No growth of the mean plasma density was indicated by the cavity diagnostics at this time.

The time delay t_d of the anomalous phenomena appearance is dependent on the pump power, magnetic field and initial electron density. At a lower pump power, the time delay increases, as it is seen in Fig.2c. Assuming that the inverse value of t_d characterizes the growth rate of a parametric instability responsible for the anomalous absorption we plot a dependence of this parameter on the pump power. As it is seen in Fig. 3 (circles), the threshold density needed for switching on of the anomalous phenomena is about 55 W. The threshold of the anomalous phenomena onset increases with electron density decreasing, whereas its growth rate decreases, as it is shown in Fig. 3, for volume average plasma density 4×10^9 cm^{-3} by triangles.
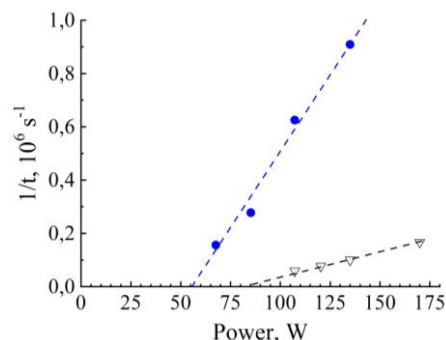

Fig. 3. Inverse time of anomalous absorption establishment against pump power.

Localization of the microwave absorption region in the filament was determined by recording the transverse distributions of the plasma glow intensity with temporal resolution. Fig. 4a (curve 1) presents the luminosity distribution in the plasma column on the 0.5 microsecond. Its maximum is on the filament axis. Then light intensity increases with tim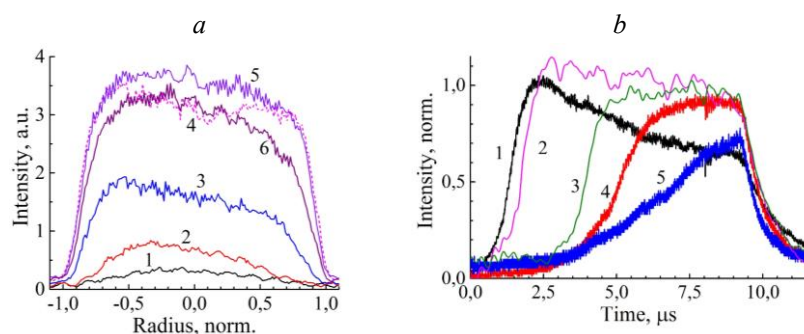e and its transverse profiles become wider. It shows that absorption takes place along the whole plasma diameter. It should be noted that no evidence of the anomalous absorption is registered at distance outside waveguide volume more than 10 cm by electron density measurement utilizing the cavity method. As to the plasma luminosity measurements, they have shown the growth outside the waveguide. In Fig. 4b, the normalized light emission waveforms at different distances from waveguide axis are presented. As it is seen, the increase of light emission takes place with a substantial time delay which is growing with increasing of the distance from the waveguide. The time delay out of the waveguide is measured in the microsecond range, which is typical for diffusion, but not for wave propagation processes. It should be also mentioned that disturbances of the plasma luminosity are absent at distances larger than 9 cm. Taking into account these measurements we can conclude that the absorption area is localized in the filament inside the waveguide.

Fig. 4. (a) Transverse profiles of light intensity in different time: 1 – 0.5 μs, 2 – 1.0, 3 – 1.5, 4 – 2.0, 5 – 3.0 and 6 – 5 μs. (b) Ligth intensity waveforms in different axial points: 1 – waveguide center, 2 – 2 cm from center, 3 – 5 cm. 4 – 8 cm and 5 – 9 cm

Based on experimental values of the reflection coefficient (Fig. 2b) we can estimate the mean electron density variation during the pump pulse using it as a fitting parameter in computations performed with a help of the HFSS software. Thus at the pulse beginning, the density supposed in computation uniform in radii, is estimated as 1.7×10^{10} cm^{-3}. It is close to value in the initial plasma obtained in experiment using the cavity diagnostics. The computed transmission coefficient in this case is close to the experimental one, as well. The collision frequency in this simulation we assume to be 10^7 c^{-1}.

After the anomalous absorption switch on, a reflected signal increases. It can be explained by the pump power anomalous absorption, electron density growth and redistribution due to the absorption. Since Ansys HFSS software does not account for the anomalous absorption effect, the estimations of electron density at $t = 2$ μs and 7 μs were performed taking into account only reflected signal (star in Fig. 2b). The obtained values of the mean electron density in this case is 2×10^{11} cm^{-3} and 3×10^{11} cm^{-3}, correspondingly. The calculated transmission coefficient (open circles) here is much higher than the experimental one and can be used to characterize the value of absorbed power.

The efficiency of the anomalous microwave power absorption is determined from the microwave power balance: $P_0 = P_t + P_r + P_h + P_{abs}$, where P_{abs} is the absorbed power. The absorption rate k_{abs} is obtained from this expression as $k_{abs} = 1 - (P_t + P_r + P_h)/ P_0$. According to measurements results presented in Fig. 5, the absorption coefficient varies drastically during the pump pulse. It increases and reaches 30-35% at $t = 2$ μs and achieve saturation at about 20% level at $t > 4$ μs.

It should be mentioned that the determined anomalous absorption rate is smaller than the value obtained for the case of the X-mode pump [5], which was as high as 80% just after the absorption onset and saturated at the level of 45%. The minimal power threshold of these phenomena is a factor of 2 higher than in the case of the X-mode pump [5]. These observations could be attributed to the different direction of pump wave electric field in respect to the magnetic field leading to different value of the plasma nonlinear susceptibility [8]. The anomalous absorption was observed in a wide range of plasma densities and no clear density limit was observed associated for instance with a critical value for the half the pump frequency. As a theoretical

Fig. 5. Time evolution of absorption coefficient.

analysis shows, the parametric decay instability leading to excitation of two electron plasma waves possessing substantially different frequencies could be responsible for the observed anomalous effects. The frequency of the first wave should be equal to the UH resonance frequency in the plasma volume, whereas the frequency of the second wave should be smaller than the maximal electron plasma frequency in the plasma volume. The power threshold for excitation of these waves by the ordinary pump wave is predicted at a level smaller than 100 mW.
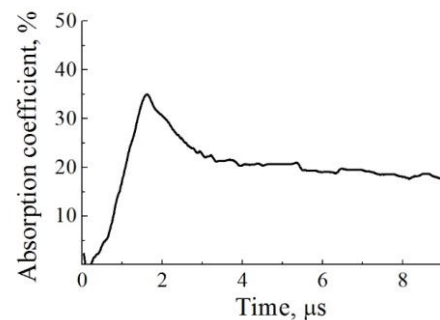
Acknowledgements

References

[1] S.K. Nielsen, M. Salewski, et al., Plasma Phys. Control. Fusion, 55, 115003 (2013).
[2] Martínez M, Zurro B, Baciero A, D. et al. Plasma Phys. Control. Fusion **60** 025024 (2018)
[3] E.Z. Gusakov and A.Yu. Popov, Physics of Plasmas, **23,** 082503 (2016)
[4] A. Altukhov, et. al., EPJ Web of Conferences, **157**, 03050 (2017).
[5] A. B. Altukhov et al. EPL,   **126** (2019) 15002
[6] https://www.ansys.com/products/electronics/ansys-hfss.
[7] https://www.bolsig.laplace.univ-tlse.fr/download.
[8] E. Gusakov, A. Popov, P. Tretinnikov JETP Letters **108**, 2, (2018)