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Experimental investigation of the UHR nonlinear wave phenomena

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In recent years, considerable attention has been attracted by the problem of new RF schemes for plasma heating in spherical tokamaks, where methods well developed for traditional tokamaks are not applicable. One of the schemes operating at high plasma density and comparatively low magnetic field typical for spherical tokamaks is based on linear conversion of the incident EM wave in the upper hybrid resonance (UHR). In spite of many attractive features, the UHR heating scheme possess a potential danger of anomalous reflection of incident power, because of nonlinear phenomena excitation. In particular, parametric decay instabilities (PDI) exited in UHR lead to redistribution of incident power between plasma species and can cause anomalous reflection, especially when excited at the plasma edge.

In this paper the results of UHR experiments carried out in ECR plasma in linear and toroidal systems are described. The interpretation of frequency spectra of backscattering signal possessing frequency shifted components and possible mechanisms of their generation is discussed.

Experimental results

The experiments in toroidal system have been carried out on ToriX device (major radius R = 0.6 m, minor radius a = 0.1 m, B_T = 0.3 T) [1]. Argon ECR plasma was created by low power (0.04 to 1 W) microwave source operating in the 10 GHz range and coupled to the chamber by waveguide located at equatorial plane from the high magnetic field side. When the cyclotron resonance position for pump wave is located close to the end of waveguide, a narrow toroidal column of ECR plasma with maximal density $n_e = 4.5\times10^8$ cm^{-3} and electron temperature T_e up to 20 eV is formed in the chamber. Distributions of plasma density and electron temperature in the equatorial plane obtained from Langmuir probe measurements are plotted on Fig. 1. The formation of the narrow plasma column is accompanied by generation of backscattering signal, which is observed in the waveguide. Its frequency spectrum possessing strong asymmetrical form is shown in Fig.2.

It consists of the line at the probing frequency and two well pronounced satellites. The first, narrow satellite is down shifted in frequency by about 4 MHz, whereas the second is up shifted by 24 MHz. This satellite is always accompanied by a much smaller one up shifted by 48 MHz. The frequency shift is increasing from 17 to 24 MHz with the pump power growing from 30 mW to 1W. The possible reason for the observed back scattering spectra is nonlinear parametric decay phenomena, which is most likely excited in vicinity of the UHR of the pump wave. At the low density narrow plasma distribution created by the ECR breakdown typical for the experiment the UHR is situated in front of the waveguide in the nearest vicinity of the ECR.

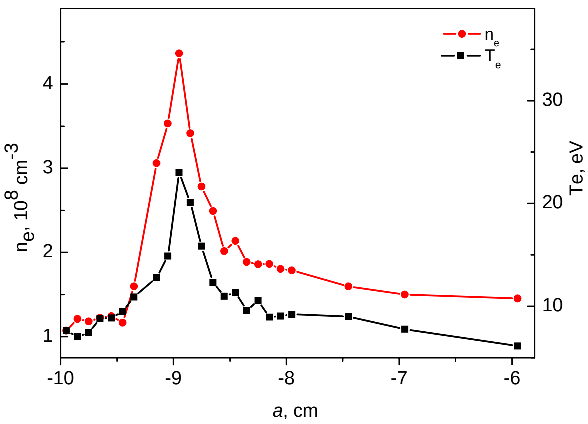

Fig.1

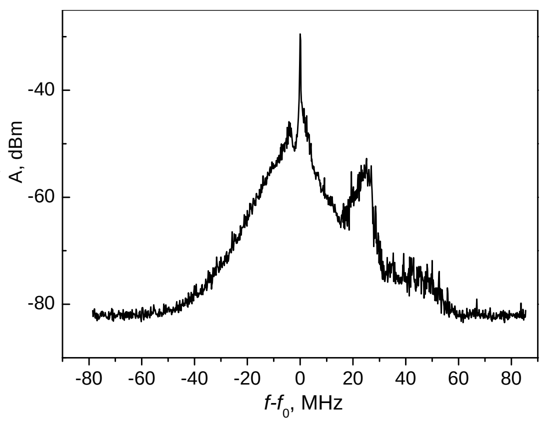

Fig.2

Both the up shifted and down shifted satellites can be interpreted as a result of the pump wave backscattering off an electron plasma wave (EPW) obeying dispersion relation $k_\perp^2 = \frac{\omega_{pe}^2}{\omega^2} k_\|^2$, and propagating correspondingly in the direction of major radius and opposite to it. The maximal EPW number is about 6 cm^{-1}, which corresponds to the strong Landau damping boarder, is sufficient to provide the backscattering in the UHR vicinity. The possible mechanism of the EPW generation can be also related to the parametric decay instability leading to excitation of the EPW and the UH wave down shifted in frequency. In the first case the later propagating towards the UHR layer is absorbed there and became non observable. It should be mentioned that a similar mechanism of the frequency up-shifted satellite excitation was investigated in our previous experiments at GRANIT plasma device, where the forward scattering PDI $l \rightarrow l' + s$ is excited in vicinity of hybrid resonance [3]. In the second case this down shifted wave is directly observable. The sharp maximum of plasma density distribution localizing the EPW is helpful for the instability onset decreasing the convective losses of the wave from the decay region [2]. Modification of plasma density profile produced with the hot filament plasma source have resulted in substantial suppression of the up shifted satellite.

UHR experiments in linear system have been performed in plasma device GRANIT [4]. The inhomogeneous ECR argon plasma at gas pressure 2×10^{-2} Torr was produced in a glass tube 2 cm in diameter and 100 cm long placed in a uniform magnetic field of 0.3 T by the 200 W and 9 GHz microwave source. The maximum density in active zone of discharge is $n_e \approx 2\times10^{12}$ cm^{-3}, and electron temperature reaches the value $T_e \approx 15$ eV.

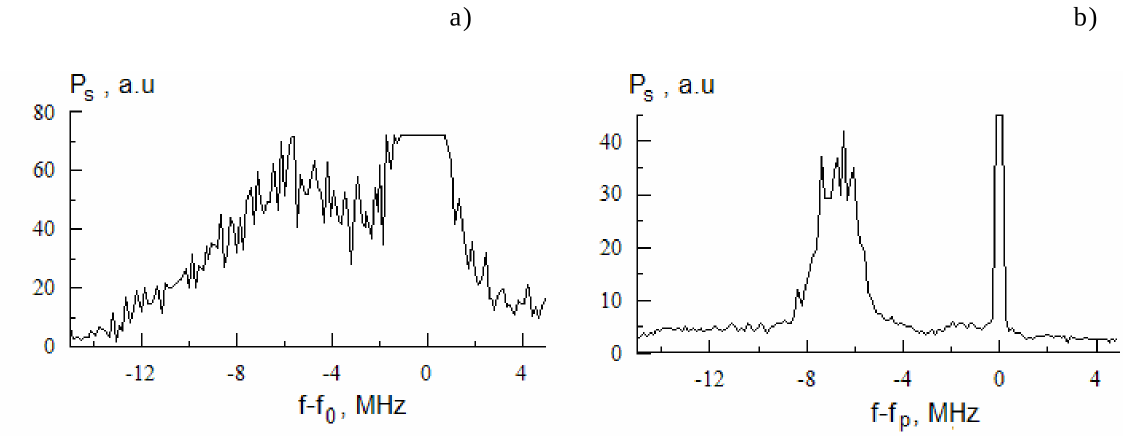

Fig. 3

The discharge was firstly created at the ECR breakdown condition, but then was sustained in rather wide range of magnetic field, much less than the resonant value. It is explained by the UH wave absorption. The role of the UHR in the power absorption is confirmed by observation of backscattering signal by loop antenna close to the active zone. Its frequency spectra having wide satellite red shifted by 6 MHz is shown in Fig. 3a. Pronounced satellite at the same frequency shift is observed also in scattering spectra of EPW specially excited in plasma (Fig.3b). This wave propagating in overdense plasma scatters off on plasma fluctuations near the UHR position was used for probing in the correlation enhanced scattering (CES) measurements of fluctuations at frequency of 6 MHz. This technique possessing the high wave number resolutions is based on the measurements of phase difference between two ES signals differing in probing frequencies [5].

The symmetrical ES scheme operating with two probing waves was used. First wave at fixed frequency f_{p1} = 2.5 GHz provides scattered signal in a reference channel and the second one with varying frequency f_{p2} from 2.15 to 2.85 GHz was used to scan the hybrid resonance position. Both scattered signals after the homodyne detection were registered simultaneously and stored. Then the Fourier spectra of signals were averaged and normalized to spectral power in each channel, and finally the cross correlation factor for chosen spectral component was calculated and plotted versus frequency difference. The dependence of the real part of the cross correlation function for 5.8 MHz shifted component is shown in Fig.4.

The fluctuations wavenumber can be estimated from experimental data by the formula: $q = \frac{2\pi}{\delta\omega_p}\frac{\partial\omega}{\partial z}$, where $\delta\omega_p = 2\pi\delta f_p$ is founded from period of oscillation in Fig.4, and z is a distance between resonance position for different probing frequencies . Finally, the fluctuations wavenumber was estimated as $q \approx 150$ cm^{-1}. This value corresponds to low frequency wave phase velocity $\upsilon_{ph} \approx 2.4 \times 10^5$ cm/s. It is smaller than the thermal electron velocity, but comparable with c_s for ion-acoustic waves propagating in decaying plasma. So, we can suppose that the backscattering of pump power in active zone of ECR discharge is explained by the parametric decay instability $l \rightarrow l' + s$, exited in vicinity of the UHR and leading to generation of small scale ion-acoustic waves.

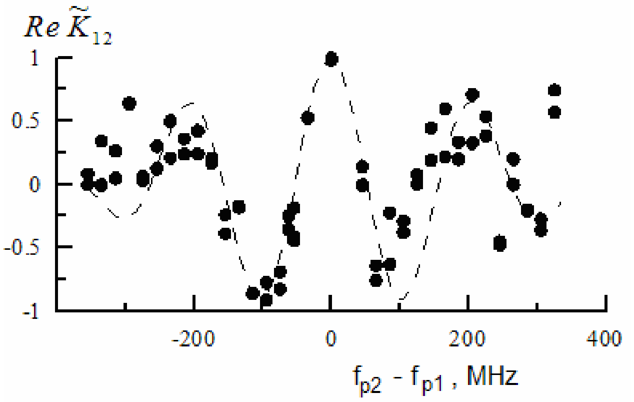

Fig.4

Conclusion

The generation of backscattering spectra is registered in the UH experiments both in toroidal system and linear device. In the toroidal system down shifted and cascade up shifted sidebands are probably caused by backscattering off the EPW, which in its turn is excited by parametric decay of UH pump wave leading to excitation of another UH wave and electron plasma wave. The sharp maximum of plasma density distribution localizing the EPW is helpful for the instability onset decreasing the convective losses of the wave from the decay region. In linear machine the excitation of UHR parametric decay instability was observed as well. It leads to backscattering of the UH pump wave and generation of small scale ion-acoustic waves with $q = 150$ cm^{-1}.

Acknowledgements

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