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Investigation of turbulence in magnetized toroidal plasma by correlative enhanced scattering diagnostics

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The microwave enhanced scattering (ES) schemes in various modifications were developed and tested for investigation of turbulence and transport in magnetized laboratory plasma and tokamaks. The efficiency of ES methods to study internal small-scale fluctuations or waves in nonuniform magnetized plasma was confirmed experimentally for wide spectra of plasma parameters [1]. The last decade the new modification – correlative enhanced scattering (CES) technique possessing high spatial resolution and high sensitivity was developed to study wavenumber spectra of fluctuations in the vicinity of upper hybrid resonance (UHR) [2-5]. In the present paper the CES technique is applied to study turbulence in low dense toroidal laboratory plasma.

Experimental results

The experiments have been performed in ToriX toroidal plasma device (major radius $R_0 = 0.61$ m, minor radius $a = 0.1$ m). A plasma with typical parameters ($n_e = 5 \times 10^{10}$ cm^{-3}, $T_e = 1.5 \div 3$ eV) and nonuniform distributions of density and electron temperature was created by a hot filament discharge at argon pressure 7.5×10^{-4} Torr and magnetic field ~ 0.3 T. Radial distribution of electron temperature obtained by Langmuir probe measurements is shown in Fig.1. Two microwave sources operating in the 10 GHz frequency range were used in experiment. Microwaves were coupled to the chamber by waveguide located at equatorial plane from the high magnetic field side. The probing waves are launched into the plasma perpendicular to magnetic field and enter the plasma as extraordinary (X) waves. If their frequency ω is properly chosen, the waves can reach the upper hybrid resonance (UHR) at a position x_{UH} defined by the resonance condition $\omega^2 = \omega^2_{UHR} \equiv \omega^2_{pe} + \omega^2_{ce}$ (where ω_{pe}, ω_{ce} are the local electron plasma and cyclotron frequency correspondingly). For our experimental conditions (comparably low plasma density) the UHR position is close to the cyclotron resonance.

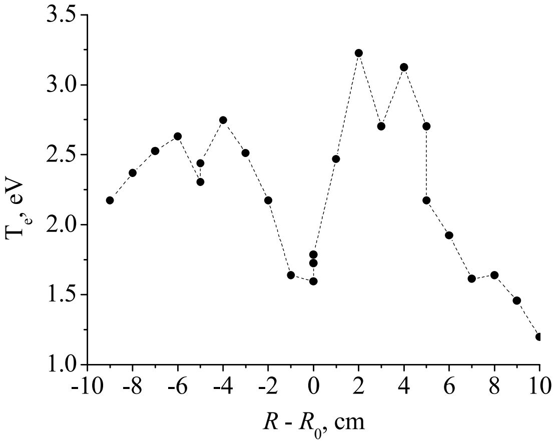

Figure 1.

Close to the UHR, the wavenumber of the incident wave, $k_i(x)$, grows rapidly up to values much higher than vacuum one $k_0 = 2\pi/\lambda_0 = \omega/c$. In the presence of small-scale density fluctuations of wavenumber q at the resonance position x_{UHR}, the probing wave is effectively backscattered when the Bragg condition $q = k_i(x) - k_s(x) = 2k_i(x)$ is fulfilled giving enhanced scattering signals [1]. The scattering is localized at the resonance region that provides high spatial resolution for the diagnostics.

Experiment have been performed for two UHR reference position $x_{UHR} - R_0 = -1.5; +1$ cm varied by toroidal magnetic field B_T. Typical backscattering spectra registered for different B_T (see Fig. 2) possess an up and down shifted asymmetrical components at 50 ÷ 800 kHz range. The amplitude of satellites linearly follows the probing microwave power. The shift of UHR position leads to a redistribution of power in backscattered spectra.

Asymmetrical CES scheme [5] utilizing two probing signals at close frequencies f_1 and f_2 with phase calibration at an intermediate frequency ζ was used in experiment. The f_1 reference frequency was fixed at 10.05 GHz, whereas the frequency in signal channel was varied in steps of 5 MHz in a range of ± 130 MHz, which corresponds to variation of the UHR position by ±0.75 cm.

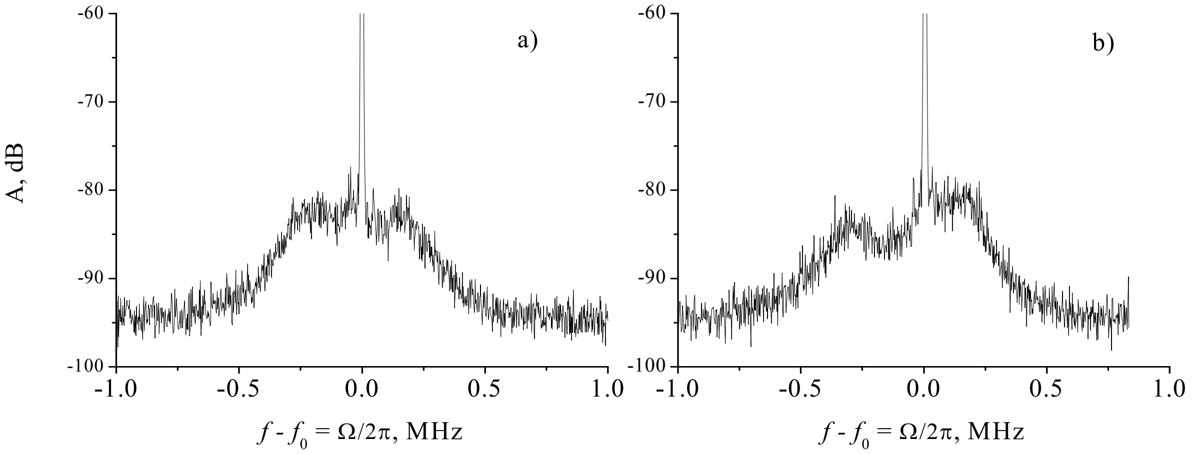

Figure 2.

Two backscattered signals were directly registered from the same guide that is used for microwave launching. These signals are corresponded to two separated UHR layers in plasma, where the waves are scattered by fluctuations with frequency $\Omega = 2\pi f_\Omega$. After the channel separation and homodyne detection at intermediate frequency ζ the signals were stored at data acquisition system for further cross-correlation analysis.

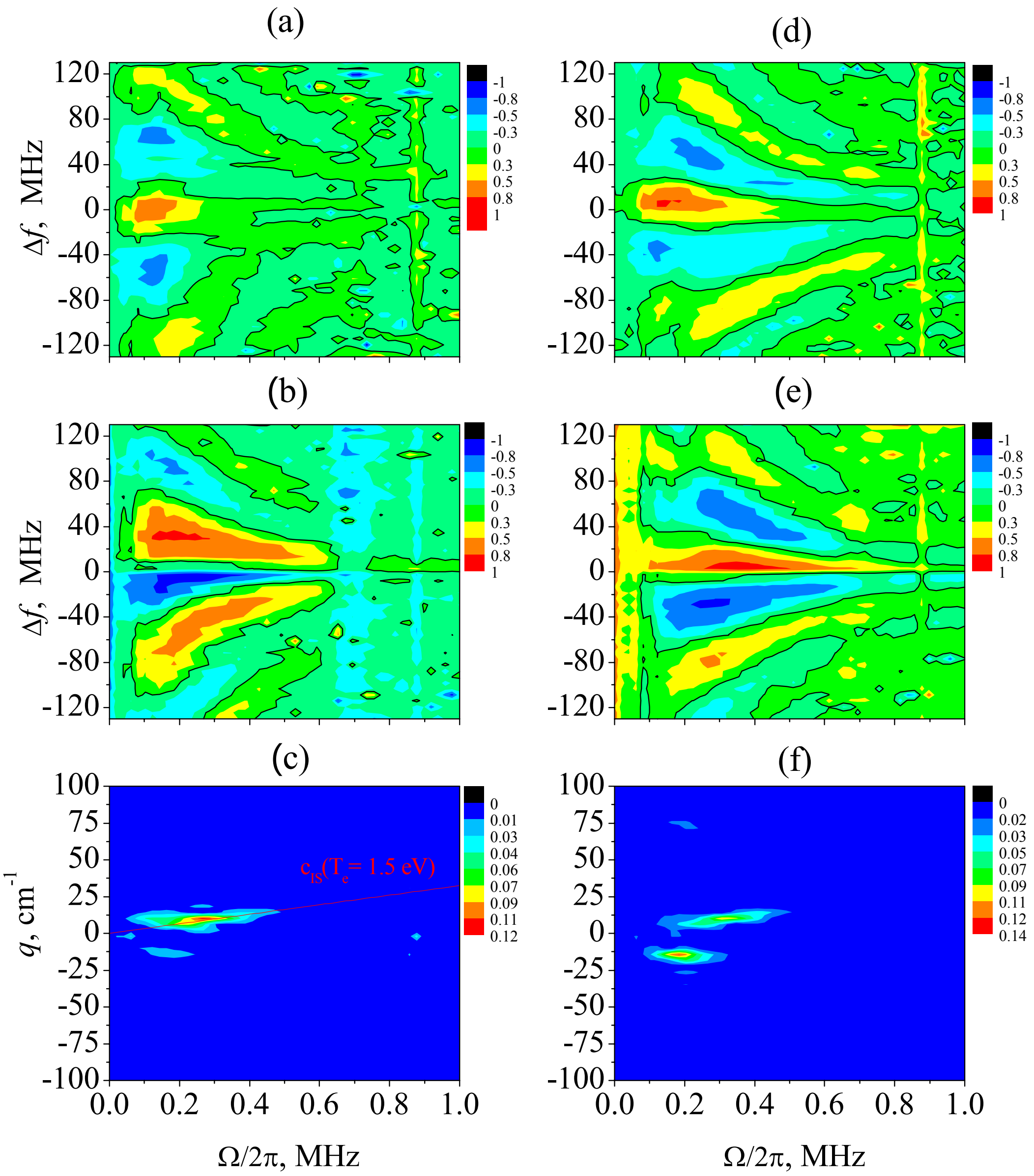

Figure 3.

In figure 3 the real (a, d) and imaginary (b, e) parts of normalized cross-correlation function (CCF) are plotted as a function of the difference of the probing frequencies Δf and turbulence frequency Ω for two different spectra observed in plasma (figure 2 (a, b)). As it is seen, the imaginary part of the CCF is comparable to the real part, both of them possess oscillatory structure and the width of the high coherency region is decreased as Ω increases. It means the turbulence wavenumbers q_R increases with Ω in the ES spectrum. ES spectrum was obtained by Fourier transform from the CCF dependence on the UHR spatial separation

$\Delta x_{\mathrm{UH}} = \zeta \partial x_{\mathrm{UH}}/\partial f_{\mathrm{i}}$ and multiplying by the signal frequency spectrum. The corresponding ES spectra are presented in figure 3 (c, f). It is clearly seen, that the coherence in ES spectra is observed in frequency region 100-500 kHz at radial wavenumbers up to 15 cm^{-1}. In case of strong asymmetry in backscattered spectra (figure 2b) two frequency regions with positive and negative q_R are observed. Their maxima are located at 200 and 300 kHz, that corresponds to frequency of up and down shifted satellites observed in frequency spectrum.

The obtained fluctuation wavenumbers are located in range of 3 ÷ 15 cm^{-1} and almost linearly grow with fluctuation frequency along line $\Omega = q_R \mathrm{c_s}$, where $\mathrm{c_s}$ – ion-sound velocity. Obtained phase velocity is about 2×10^5 cm/s that is close to the ion-sound one at electron temperature $T_{\mathrm{e}} = 1.5$ eV as measured in vicinity of the torus axis (see figure 1).

Conclusion

The new powerful diagnostics - correlative enhanced scattering technique - was applied to study fluctuations in UHR in low dense toroidal laboratory plasma. It is shown CES technique is sensitive to fluctuations observed in 100-500 kHz frequency range with corresponding radial wavenumbers up to 15 cm^{-1}. It is in a good agreement with results obtained by laser scattering diagnostics [6]. Based on the dispersion relation reconstructed from CES data one can suppose the observed turbulence has electrostatic origin.

Acknowledgements

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