Correlative Enhanced Scattering Diagnostics of Small Scale Plasma Fluctuations

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Introduction.
Enhanced Scattering (ES) diagnostics of small scale plasma fluctuations is based on the effect of scattering cross section enhancement in the Upper Hybrid Resonance [1]. High sensitivity and localization of measurements are among its merits. The RADAR modification of this technique was proposed recently to improve the diagnostics wave number resolution. In spite of evident progress of RADAR ES [2], it suffers from essential losses of scattered signal due to the amplitude modulation of the incident wave.
The correlative modification of ES technique [3], in which merits of the standard ES scheme are completed with reasonable wave number resolution, is under development in the present paper. The correlative approach to ES diagnostics is based on the ES signal dependence on the fluctuation phase in the UHR point [3]. The probing is performed there by two waves. The frequency of the first, reference one, is constant, where as the frequency of the second one is varied, providing the spatial scan of the UHR point. In the case of random density perturbations, if the density turbulence is statistically stationary and homogeneous, its spectra could be studied by correlation technique for reconstruction of the density turbulence frequency and wave number spectra. The theoretical background for it is provided by relation between Cross-Correlation Spectrum (CCS)

$$K(\omega_1,\omega_2,\Omega_1,\Omega_2)\delta(\Omega_1-\Omega_2)=\left\langle A_s(\omega_1,\Omega_1)A_s^*(\omega_2,\Omega_2)\right\rangle \Big/ \left|A_i^2\right| \quad (1)$$

and the fluctuation spectrum $\left|\delta n\right|^2_{q,\Omega}$. Here ω_1 = ω_i and ω_2 == $\omega_i+\nu$ - frequencies of the probing waves, Ω_1 and Ω_2- spectral harmonics of a turbulence, A_s-scattered signal, A_i-probing signal. Taking into account that

$$\left\langle \delta n_{q,\Omega}\delta n^*_{q',\Omega'}\right\rangle=(2\pi)^4\left|\delta n\right|^2_{q,\Omega}\delta(\vec q-\vec q\,')\delta(\Omega-\Omega') \quad (2)$$

and using the expression for A_s in form [4]

$$A_s=\frac{i\omega_i A_i}{16\pi\, n_e}\int U(\vec q)\delta n_{q,\Omega}e^{-iq_x x_{UH}(\omega_i)}\frac{d^3\vec q}{(2\pi)^3}, \quad (3)$$

where
$$U(\vec q)=\int \mathrm{E}^+(\vec r)\mathrm{E}(\vec r)e^{-iq_z z-iq_x[x-x_{UH}(\omega_i)]-iq_y y}d^3\vec r, \quad (4)$$

q_x, q_y and q_z are fluctuation wavenumbers, x_{UH}- a position of upper hybrid resonance, we obtain CCS in the following form

$$K(\omega_1,\omega_2,\Omega_1,\Omega_2)=\left(\frac{\omega_i}{16\pi n_e}\right)^2\left|A_i\right|^2\int\frac{dq_y dq_z}{(2\pi)^2}\int_0^\infty\frac{dq_x}{2\pi}\left|U\right|^2\left|\delta n\right|^2_{q,\Omega}e^{iq_x(\omega_2-\omega_1)\frac{\partial x_{UH}}{\partial\omega}}, \quad (5)$$

the factor $U(\vec q)$ is determined by the microwave field $\mathrm{E}^+(\vec r)\mathrm{E}(\vec r)$ structure near the UHR.
The fluctuation spectrum averaged across the inhomogeneity direction

$$\left|N\right|^2_{q_x,\Omega} = \int \frac{dq_y dq_z}{(2\pi)^2} \left|U\right|^2 \left|\delta n\right|^2_{q,\Omega} \tag{6}$$

is given by Fourier transform of (5) as

$$\left|N\right|^2_{q_x,\Omega} = \left(\frac{16\pi n_e}{\omega_i}\right)^2 \int K(\omega_i, \omega_i + \nu, \Omega_1, \Omega_2) e^{-iq_x \nu \frac{\partial x_{UH}}{\partial \omega}} d\nu \quad , \tag{7}$$

showing the possibility of the density perturbation from the CCS data. The present paper is devoted to the experimental confirmation of this possibility.

Experimental results.

The experiments were performed on linear plasma set-up [1]. A plasma with a nonuniform radial density distribution was produced with the aid of a hot cathode plasma source with magnetic multipoles, in a 5 cm diameter and 2 m long tube filled with argon at pressures (6-9) $*10^{-4}$ torr and placed in magnetic field 0.1 T. The average electron density was $n_e=10^{10}$ cm^{-3} and the electron temperature T_e=2-4 eV. Spontaneous turbulence has been a target fluctuation in the experiments. The scattered signal had a continuous spectrum with frequencies shifted up and down by 1.5-4 MHz [1]. This turbulence was studied recently by RADAR-technique [2] and was found to have an ion-acoustic dispersion. However the turbulence spectrum was not determined in [2].

Two probing waves produced by two oscillators in the frequency range of about 2.4 GHz were launched into the plasma as extraordinary modes by an open waveguide antenna. The frequency of one oscillator was fixed, while another one was varied. The scattered signal was received by another antenna located adjacent to the transmitted one and divided into two channels. The homodine conversion was used in both channels. The microwave power, penetrating from transmitting antenna into receiving one, was utilized as a reference signal. To split scattered signals related to different probing frequencies narrow band microwave reject filters were used in each channel. After homodine conversion signals in both channels were filtered in the 0.3-1.8MHz frequency band and fed to the digital oscilloscope and then to computer. The circuit enabled us to make measurements starting from 3 MHz shift of probing frequencies which corresponds to 0.1 mm spacing of UH resonances. Measurements have been carried out for two experimental situations: when the downshifted part of the spectrum dominated the up-shifted one (asymmetric spectrum) and when they were about equal (symmetric spectrum).

The computer data processing includes dividing of the recorded temporal realizations of the scattered signal into smaller sample intervals of 3μs length for Fourier transform and further statistic averaging. The following form of (1) was used in line with this procedure:

$$K_{norm}(\Omega, x_1, x_2) = \sum_i A_{S1}(\Omega, x_1) A^*_{S2}(\Omega, x_2) \Big/ \sqrt{\sum_i \left|A_{S1}(\Omega, x_1)\right|^2 \sum_i \left|A_{S2}(\Omega, x_2)\right|^2} \tag{8}$$

where x_1 and x_2 are radial positions of the UH resonances and summation is performed over 3 μs intervals. The δ-correlation between different spectral components Ω_1 Ω_2 has been checked during the data analyses. The cross-correlation spectrum (8) has been calculated for different turbulence frequencies Ω and different probing frequency shifts ω_1-ω_2 , providing the scan of the UHR separation x_1-x_2 . Fig.1 shows real and imaginary parts of CCS for asymmetric (a,b) and symmetric (c,d) turbulent frequency spectra at frequencies 0.3 MHz and 1.2 MHz, plotted versus the UHR separation distance x_1-x_2, calculated using UHR equation and experimental density profile. As it is seen the decay of cross-correlation with growing UHR separation is accompanied by oscillations. The CCS real part is comparable to the imaginary one for symmetric spectrum, where as it is much larger in the asymmetric case. It is consistent with the strong spectrum asymmetry in the first case and nearly symmetry in the second one. Inverse Fourier transform of these dependencies according to (7) produces the density fluctuation wave number spectra multiplied by enhancement factor q^2 , which are shown in Fig.2. These spectra for all frequencies posses dominate maximums, which increases with increasing fluctuation frequency in agreement with ion-acoustic dispersion relation. As it is seen in Fig.2 the frequency spectral symmetry (b) or asymmetry (a) is reproduced in the wave number spectra.

The density turbulence spectrum $\left|\delta n\right|^2_{q,\Omega}$ (in arbitrary units) recalculated from the data of Fig.2, taking into account the ES enhancement factor q^2, is shown in Fig.3 Unlike the spectra, shown in Fig.2, it is no longer normalized and describes both the wave number and the frequency spectral dependencies.

Conclusions.

The correlative UHR scattering diagnostic was tested in the model proof of principle experiment on the linear plasma device and shown to be a feasible tool for local study of the small scale turbulence wave number and frequency spectra in inhomogeneouse magnetized plasmas. The applications of this technique to tokamak experiments could be recommended.

Aknowlegements.

The paper was supported by RFBR grants 96-02-17913, 96-15-96367.

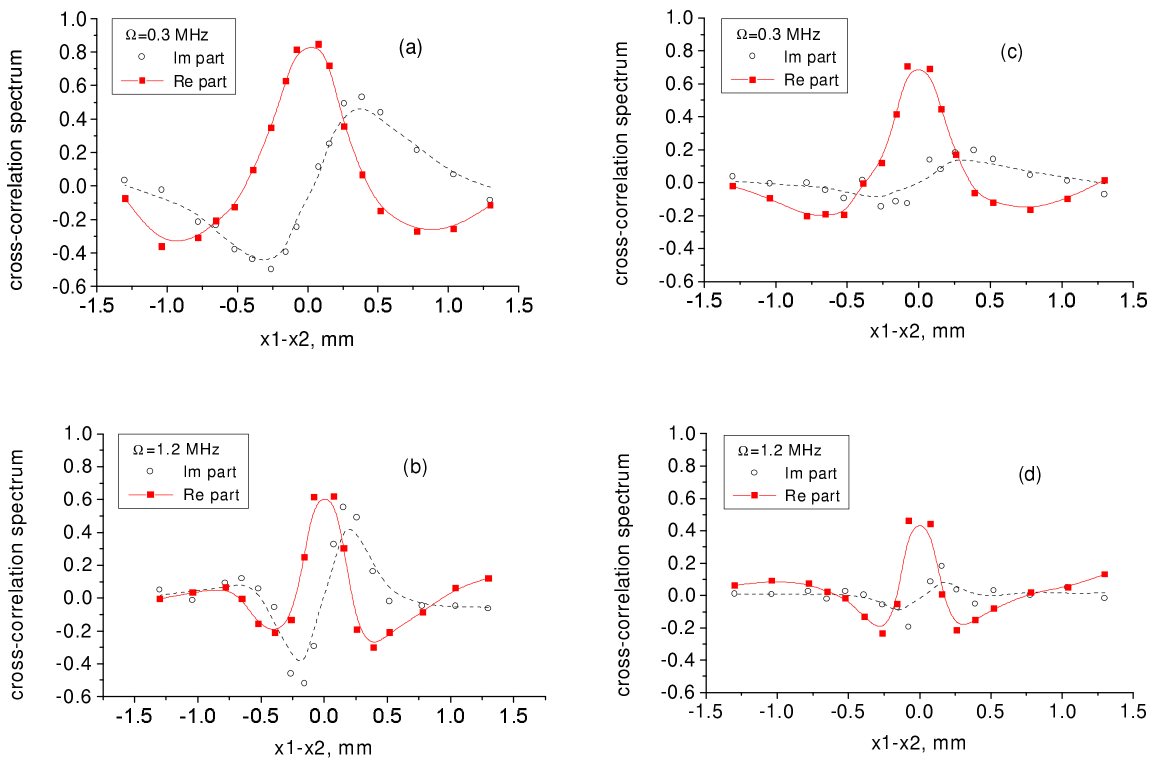

Fig.1. Cross-correlation spectra of plasma turbulence

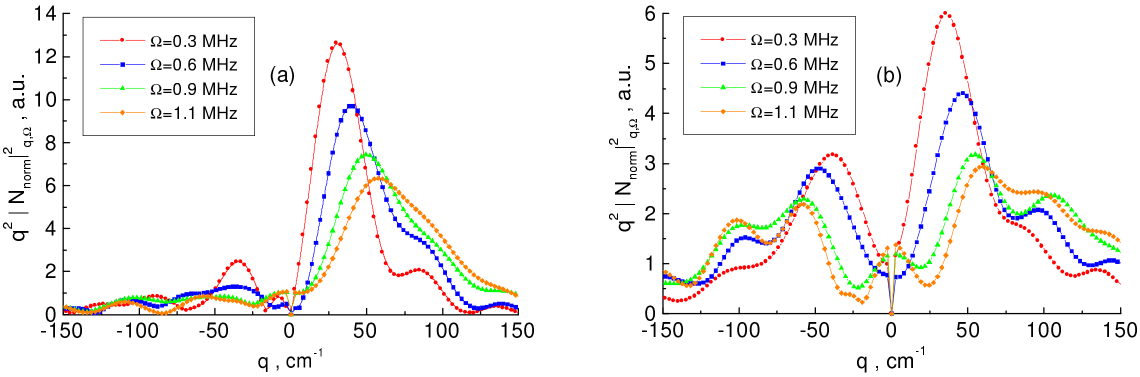

Fig.2. Normalazed density turbulence spectra, multiplied by the enhancement factor

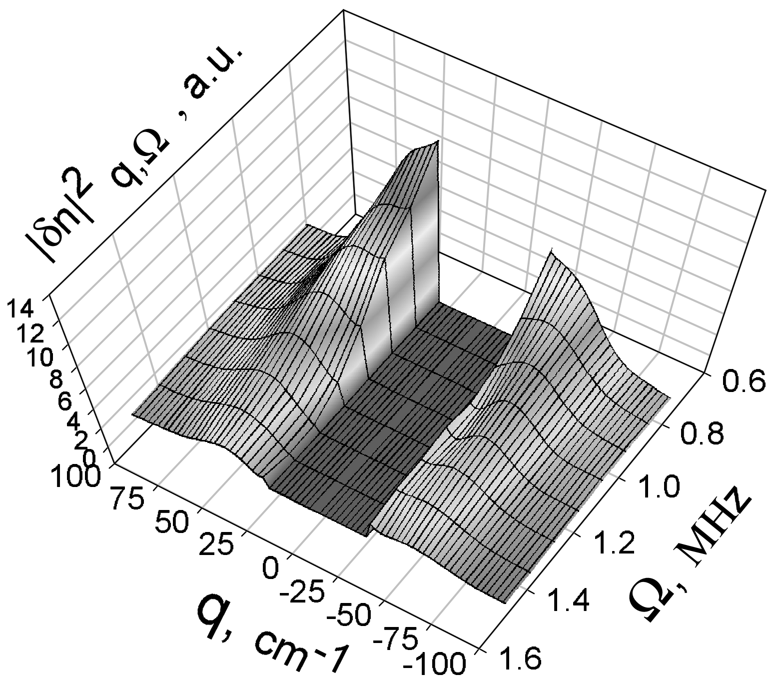

Fig.3. The dencity turbulence spectrum

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