Evolution of turbulence wave number spectra during helium puffing into the FT-2 tokamak hydrogen discharge

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According to theoretical expectations [1], the wave number spectra (q-spectra) of drift wave turbulence in a tokamak in a wide q-range corresponding to the so-called inertial interval between the high growth rate and high dissipation region should obey a power law taking a Kolmogorov-like form. Experimental observations carried out in limited q-range usually confirm this prediction, however measurements specially performed by CO_2 laser scattering in a wide range [2, 3] rather give evidence for exponential spectrum dependence on q. These poor spatially localised measurements were recently confirmed at the FT-2 tokamak [4] where observations of robust exponential turbulence q-spectra performed with correlative enhanced scattering (ES) diagnostics [5-7] characterised by fine spatial and reasonable q-resolution were reported. It was found that during the dynamic current ramp up discharge the spectrum could be described by universal dependence $|n|^2_{q_r} \sim |n|^2_0 \exp\{-q_r L\}$ in the range of 3-4 orders of amplitude, where $|n|^2_0$ is related to the turbulence level and L is a typical turbulence scale length which appears to be in the range of (1-2)ρ_i.

In the present paper we report the results of dynamic experiments carried out at FT-2 tokamak (R = 55 cm; a = 7.9 cm; B_t = 2.2 T; I_p = 22 kA) in hydrogen discharge with intensive helium puffing. The purpose of the experiment was to check the exponential spectra robustness and the physical meaning of the L parameter, in particular, its dependence on the ion Larmor radius which is a factor of 2 smaller for the He^{1+} component. The plasma possessing at the quasi stationary stage of discharge (25÷40 ms) density $n_{e0} \sim 3\times10^{13}$ cm^{-3} was formed by pulse helium puffing into preliminary hydrogen discharge with $n_{e0} \sim 1.5\times10^{13}$ cm^{-3}. Density of ion species was determined from the results of modeling [8], based on observed spectral line emission profiles and experimentally measured plasma parameters (T_e, n_e, T_i). This approach takes into account Z_{eff}, calculated by ASTRA code, plasma quasi

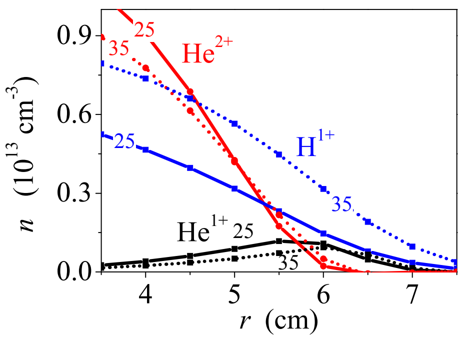

Fig. 1. Radial distribution of H^{1+}, He^{1+}, He^{2+} densities.

neutrality and ionization recombination (IR) balance for ion species. A few assumptions have been done: (1) density of the main impurity ion O^{8+} remains the same after He-puffing (which is supported by dynamics of oxygen spectral lines); (2) Z_{eff} depends on He^{1+} coupled with H^+, He^{2+} and O^{8+} and is uniform over r; (3) IR balance equations $\frac{\partial n_j}{\partial t} = -\frac{1}{r}\frac{\partial}{\partial r}(r\Gamma_j) + S_j$ [9] for $j = \{e, H^+, He^{1+}, He^{2+}\}$ are treated as quasi stationary; (4) particle fluxes $\Gamma_j = -D_{eff}\, dn_j/dr$, assumed anomalous with $D_{eff} = 2$ m^2/s. Densities of He^{1+}, He^{2+} and H^+ ions were evaluated by IR balance code using H and He (at the plasma boundary) atom density as fitting parameters. The modeling was performed using atomic database for helium and hydrogen systems available through published data (cross-sections, ionization, recombination, charge-exchange and excitation rate coefficients). Measured intensity of corresponding spectral lines (HeII: 468.6 nm, H_α: 656.3 nm, HeI: 667.8 nm) was used for verification of the simulation data. The determined radial distributions of H^+, He^{1+}, He^{2+} are shown in Fig. 1 for $t = 25$ ms and $t = 35$ ms. As it is seen there, the He^{1+} density is comparable to the proton density and exceeds the He^{2+} concentration only in the edge region at 5.5 cm < r < 7 cm and in the early stage of the discharge, at $t = 25$ ms. Later the proton density grows faster and exceeds the He^{1+} density everywhere, as it is shown in Fig. 1 for $t = 35$ ms.

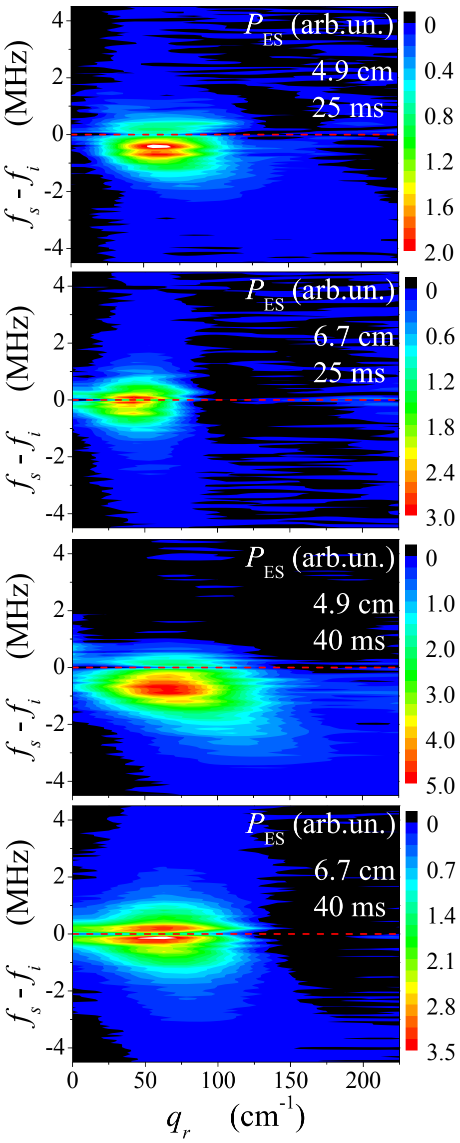

Fig. 2. The ES signal spectra.

The turbulence radial wave number spectrum was measured by correlative ES diagnostic utilizing X-mode probing performed out off the equatorial plain from high field side. It registers back scattering off density fluctuations with radial wave numbers $q_r > 4\pi f_i/c$ occurring in the very vicinity of the upper hybrid resonance (UHR). The q_r-spectrum of fluctuations contributing to the ES signal is obtained using the correlation analysis of simultaneously measured ES signals at different probing frequencies (f_i = [57-64] GHz and $f_i + \Delta f$, where $\Delta f = \pm$[20..400] MHz) with the following reconstruction procedure introduced in [5] and then applied in [6, 7] to different experiments. The determined dependence of the normalized cross-correlation function (CCF) of two ES signals on Δf, proportional to the corresponding UHR spatial separation, is Fourier transformed and multiplied by the ES homodyne spectrum to obtain the ES spectrum. The q_r-spectrum of the turbulence is then obtained as a result of fitting procedure from the ES spectrum representation in the form of an integral over turbulence poloidal and radial wave numbers accounting for the turbulence spectrum, the ES efficiency and the antenna diagram in the UHR [5]. The ES spectra obtained in the experiment are shown in Fig. 2 for two radial positions at $t = 25$ ms and $t = 40$ ms of the discharge. As it is seen, at $t = 25$ ms the ES spectrum is much broader in the gradient zone of the discharge ($r = 4.9$ cm) than at the edge ($r = 6.7$ cm), whereas at $t = 40$ ms the difference is not that pronounced.

The turbulence q-spectra corresponding to the ES spectra, shown in Fig. 2 are presented in Fig. 3. The wave number spectra given by pink points correspond to values maximal along the (f_s - f_i)-direction, whereas blue points represent values averaged over the frequency interval [-1.9, 1.9] MHz. As it is clearly demonstrated in Fig. 3, at $t = 25$ ms the wave number spectrum measured at the edge is much steeper than in the gradient zone, whereas at $t = 40$ ms the difference is less pronounced.

Following [4] and approximating the wave

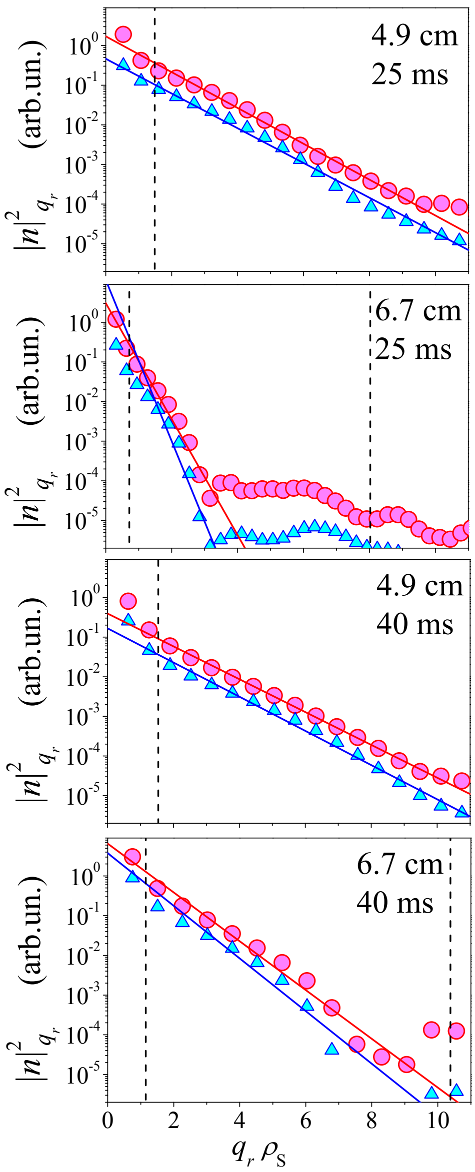

Fig. 3. The turbulence q-spectra.

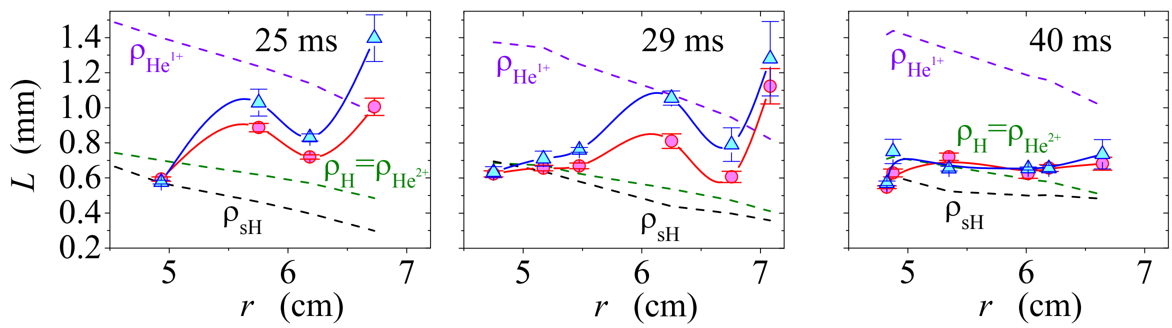

Fig. 4. The turbulence scale length versus radii.

number spectra by exponential dependencies (see linear curves on Fig. 3) over more than three orders of magnitude we obtain the turbulence scale length parameter L dependence on radius shown in Fig. 4. As it is seen there, in the early discharge stage (at $t = 25$ ms and $t = 29$ ms), characterised by substantial density of He^{1+} at the edge, parameter L is varying from the value close to the proton Larmor radii (ρ_H) in the gradient zone at $r = 5$ cm to the value substantially exceeding it and close to the He^{1+} Larmor radii ($\rho_{He^{1+}}$) at the edge at $r = 7$ cm. On contrary, in the discharge final stage (at $t = 40$ ms), when protons dominate all over the plasma, parameter L is close to the proton Larmor radii both in the gradient zone and at the edge $L \sim \rho_{He^{2+}} = \rho_H$. It is interesting to note that the second parameter of the exponential spectrum $|n|_0^2$, related to the turbulence level, also experiences significant variation accompanying decrease of the relative He^{1+} concentration. As it is demonstrated in Fig. 5, it decreases by a factor of three at the plasma edge, but grows by an order of magnitude in the gradient zone.

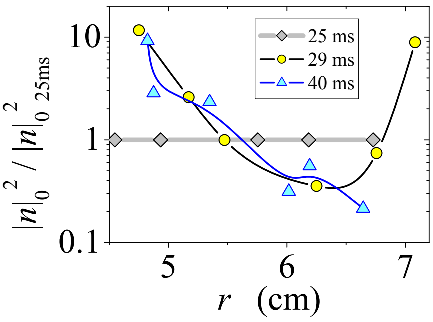

Fig. 5. The turbulence level variation.

Conclusions

Implementation of the correlative ES technique at FT-2 tokamak has resulted in measurements of both frequency and wave number spectra of small-scale micro turbulence. It is found that during the dynamic He puffing discharge the turbulence possesses a wide q-spectrum which could be approximated by universal exponential dependence in the range of 3-4 orders of amplitude characterized by two parameters – the turbulence level and scale length. The second parameter is found to be close to the Larmor radii of the dominating ion. It decreases by a factor of two when the He^{1+} concentration decreases substantially at the periphery.

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