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Evolution of turbulence exponential wave number spectra during transition to improved confinement triggered by current ramp up at FT-2 tokamak

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According to theoretical predictions [1], the wave number spectra (q-spectra) of drift wave turbulence in a tokamak plasma with 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, where the q-spectrum looks linear in double logarithmic scale: $\lg(|n|_q^2 / |n|_{q_0}^2) = -\alpha \lg(qL)$. Experimental observations carried out in limited q-range usually confirm this prediction. The measurements performed by CO_2 laser scattering in a wide q-range shifted to small scales [2] gave an evidence for a knee-like spectrum composed of two power law spectra with different indexes α. An overlap of the investigated q-range with both inertial interval and turbulence dissipation region would be a possible explanation for this observation. However, as it was shown in [2], when plotted in semi logarithmic scale, the observed spectrum fitted surprisingly well the exponential dependence on wave number $\lg(|n|_q^2) \sim -qL$. This intriguing observation performed by CO_2 laser scattering, unfortunately limited in spatial resolution, is appealing for more detailed studies of the small-scale drift turbulence q-spectra by more precise diagnostics.

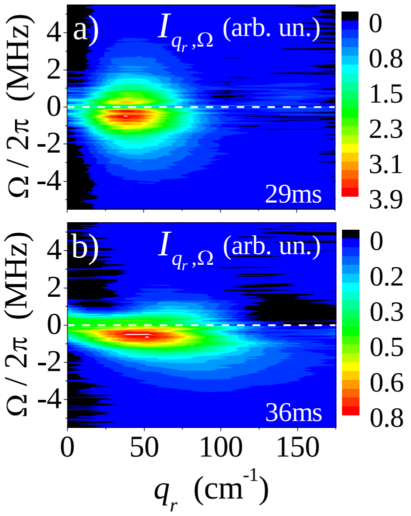

Fig. 1. *ES spectra for (a) 29 and (b) 36 ms.*

In the present paper we report observations of both frequency and q-spectra of turbulence performed with correlative enhanced scattering (ES) diagnostics characterised by fine spatial and reasonable q-resolution [3]. The ES diagnostic utilizes X-mode probing performed out off the equatorial plain from the high field side. It measures 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 observed Doppler frequency shift of the ES signal is utilised to determine the

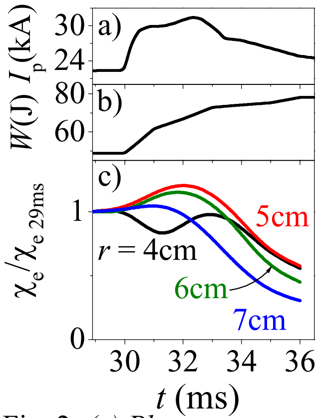

Fig. 2. *(a) Plasma current, (b) energy content, (c) electron thermal conductivity dynamics.*

poloidal plasma rotation velocity. The q_r-spectrum of fluctuations contributing to the ES signal is obtained from the correlation analysis of simultaneously measured ES signals with different probing frequencies $f_i = 54\text{-}65$ GHz and $f_i + \Delta f_i$ ($\Delta f_i = \pm[20..400]$ MHz). The following reconstruction procedure introduced in [3] was applied in [4, 5] to different experiments. The determined dependence of the normalized cross-correlation function (CCF) of two ES signals on Δf_i, proportional to the corresponding UHR spatial separation, is Fourier transformed and multiplied by the ES homodyne spectrum to obtain the ES spectrum $I_{q_r,\Omega}$ (fig. 1). 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 wave number accounting for the turbulence spectrum, the ES efficiency and the antenna diagram in the UHR.

The measurements are carried out at the FT-2 tokamak ($R = 55$ cm; $a = 7.9$ cm; $B_t = 2.2$ T, $n_e(0) < 5\times10^{19}$ m^{-3}, $T_e(0) < 500$ eV) in fast (20 MA/s) current ramp up (CRU from 22 kA to 32 kA) experiment (Fig. 2). The important feature of this scenario is the observed suppression of anomalous electron transport. Namely, investigation of electron and ion temperature, electron density profiles and radiation losses evolution together with ASTRA code modelling allows us to conclude that the effective electron thermal conductivity coefficient χ_e was suppressed in the discharge at 4-6 ms after CRU and, in particular, decreases by a factor of 2 at the plasma periphery. It should be stressed that the χ_e behaviour there (Fig. 3a) is well correlated with the ES signal power suppression by 30-40%. The level of the ES signal power integrated in [-2..+2] MHz frequency band was measured for different UHR radial positions from $r = 5.5$ cm till 7.5 cm. The evolution of the obtained profiles normalized to the profile at 29 ms (before CRU) is shown in Fig. 3b.

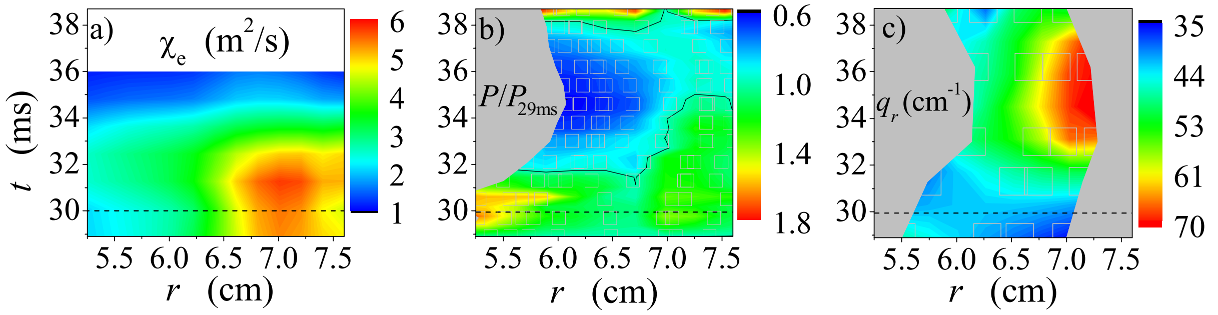

Fig. 3. *(a) Electron thermal conductivity, (b) normalized ES signal power (gray squares: measuring points; solid black curves: $P/P_{29ms}=1$), (c) radial wave number at the ES spectrum maximum.*

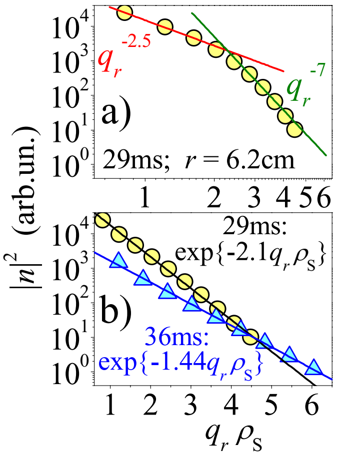

Fig. 4. *Turbulence q-spectra (a) for 29 ms in double- and (b) for 29 and 36 ms in semi-logarithmic scale.*

Unfortunately, the ES signal suppression could not be directly interpreted in terms of the density fluctuation level drop, because of the strong ($S_{ES} \sim q_r^3$) dependence of the ES efficiency on the turbulence radial wave number. Nevertheless, investigation of the ES $I_{q_r,\Omega}$ spectrum evolution during the CRU experiment provides additional arguments in favour of the turbulence suppression. Namely, as it is clearly seen from the comparison of Fig. 1a and Fig. 1b, the $I_{q_r,\Omega}$ spectrum determined at $r = 6.2$ cm experiences a substantial shift to higher q_r after CRU. The approximation surface $q_r(r, t)$ demonstrating the evolution of q_r values corresponding to ES $I_{q_r,\Omega}$ spectra maximum is shown in Fig. 3c. Since the drop of the UHR BS signal (Fig. 3b) is accompanied by an increase of q_r from 40 cm^{-1} till 70 cm^{-1} (Fig. 3c) and thus by a strong increase of the ES efficiency, one could conclude that the real drop of the turbulence level was even higher than the ES signal power suppression, observed in the experiment. In addition to the above rough analysis we have also reconstructed the turbulence q_r-spectra at different radii and followed their evolution during CRU. The turbulence q_r-spectra were determined for $8 > q_r\,\rho_i > 0.8$ at a distance 1-3 cm from the limiter (ρ_i - ion gyroradius). Plotted in double logarithmic scale (Fig. 4a) they are usually knee-like, suggesting that the turbulence cascading to small scales where damping takes place is measured. However when shown in semi logarithmic scale (circles in Fig. 4b), similar to [2], they fit linear dependence surprisingly well. Moreover, it was found that in the whole range of radii accessible for ES, during 13 ms after CRU 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 (Fig. 4b), where $|n|^2_0$ is related to the turbulence level and L is a typical turbulence scale length. The evolution of these parameters is shown in Fig. 5, where $|n|^2_0$ is normalized by its value at 29 ms. Both parameters are found to decrease substantially at 2-6 ms after CRU simultaneously with strong growth of the poloidal plasma rotation velocity gradient in the edge region. Estimated from the ES signal Doppler frequency shift, the later increased from 25 kHz to 190 kHz (Fig. 6a).

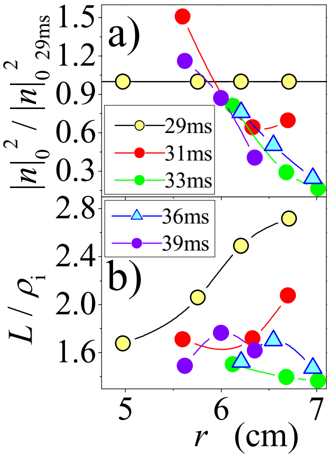

Fig. 5. *(a) Turbulence level and (b) spatial scale.*

To interrelate these two effects during the CRU experiment the linear mode analysis by GS2 code [6] was performed for FT-2 discharge parameters allowing to determine the most unstable mode with frequency f and growth rate γ. The comparison of γ with the poloidal plasma rotation shear ω_E was done at $r = 6.2$ cm. As it is seen in Fig. 6b, before CRU (at 29 ms) the condition $\omega_E \le \gamma$ is fulfilled for the whole q-range which makes the development of instabilities possible. On contrary, during the current relaxation period (at 36 ms) the opposite condition $\omega_E > \gamma$ holds for turbulence with $q_\theta < 50$ cm^{-1} which, according to [7], makes turbulence suppression at these scales possible, as observed in the experiment (Fig. 5a). It should be mentioned that the decrease of the turbulence correlation length accompanying its suppression at $\omega_E > \gamma$ is also predicted by [7]. Most likely the decrease of the typical scale length L of the turbulence observed by ES diagnostic during transition to the improved confinement (Fig. 5b) may be considered as a confirmation of the above prediction.

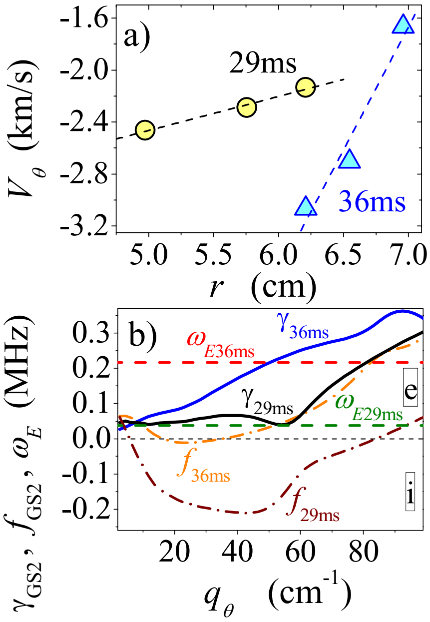

Fig. 6. *(a) Poloidal plasma velocity; (b) rotation shear, growth rate and frequency for linear modes.*

Conclusions

The implementation of the correlative ES technique at the FT-2 tokamak has resulted in measurements of both frequency and q-spectra of small-scale microturbulence. It is found that during the dynamic CRU discharge the turbulence possesses a wide q-spectrum which could be described by universal exponential dependence in the range of 3-4 orders of amplitude characterized by two parameters – the turbulence level and scale length. Both parameters are found to decrease substantially when the shear of the poloidal plasma rotation estimated from the Doppler frequency shift of the ES signal increases at the plasma periphery. Simultaneously a transition to the improved confinement resulting in suppression of anomalous electron transport is observed in the experiment.

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[1] W. Horton, *Rev. Mod. Phys.* 71, 735 (1999)
[2] P. Hennequin, R. Sabot, C. Honore, et al., *Plasma Phys. Control. Fusion* 46, B121 (2004)
[3] E.Z. Gusakov, A.D. Gurchenko, A.B. Altukhov, et al., *Plasma Phys. Control. Fusion* 48, A371 (2006)
[4] E.Z. Gusakov, A.D. Gurchenko, A.B. Altukhov, et al., *Plasma Phys. Control. Fusion* 48, B443 (2006)
[5] A.D. Gurchenko, E.Z. Gusakov, A.B. Altukhov, et al., *Nucl. Fusion* 47, 245 (2007)
[6] M. Kotschenreuther, G. Rewoldt, W.M. Tang, *Comp. Phys. Comm.* 88, 128 (1995)
[7] H. Biglari, P.H. Diamond, P.W. Terry, *Phys. Fluids B* 2, 1 (1990)