Characterization of edge turbulence in the ELM-crash-suppressed H-mode plasma

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Introduction

The crash of the edge-localized modes (ELMs) is a sudden collapse of the edge pedestal which induce relaxation of energy and particles from the confined plasma into the scrape-off layer [1]. It is a critical issue in magnetic fusion device rely on H-mode plasmas, since the heat load of the ELM crash on plasma components can be damaging. One of most popular methods to control the ELM crash is to perturb the plasma edge by adding small magnetic fields (approximately resonant with the equilibrium magnetic fields) in the edge of plasma, thereby enhancing particle transport and keeping the edge pressure gradient below crash threshold.

Despite successful control of the ELM crash, there are still many open questions concerning the mechanism of ELM crash suppression. In this letter, electron cyclotron emission imaging (ECEI) system on the Korea Superconducting Tokamak Advanced Research (KSTAR) is used to investigate the change of edge transport induced by turbulence during the period of ELM crash suppression by resonant magnetic perturbation (RMP). Especially, 2-D correlation measurement, spectral power density and dispersion relation of edge turbulence have been obtained with high resolution using correlation analysis technique.

Electron cyclotron emission imaging (ECEI) system in the KSTAR

The ECEI can be regarded as a microwave camera for measuring 2-D electron temperature fluctuations (T_e) [2]. The KSTAR ECEI system consists of vertically aligned array of 24 antennas and each antenna is connected to heterodyne detector that resolves the radiation in 8 frequency bands. Therefore the array provides $24 \times 8 = 192$ pixels image of T_e fluctuations ($\tilde{T}_e = \delta T_e / \langle T_e \rangle$, where $\delta T_e = T_e - \langle T_e \rangle$ and $\langle T_e \rangle$ is a time average). Due to flexible local oscillator and large aperture optics system, a view positition of ECEI can be focussed anywhere in poloidal cross-section with variable vertical coverage. In addition, another ECEI system by $1/16^{th}$, to extend the diagnostic capability to quasi 3-D imaging for MHD instabilities as well as correlation ECE diagnostics for turbulence measurement. For the KSTAR ECEI system, the vertical channel spacing z_0 of each samle volume is in the range of $1.4-4.0$ cm and the distance

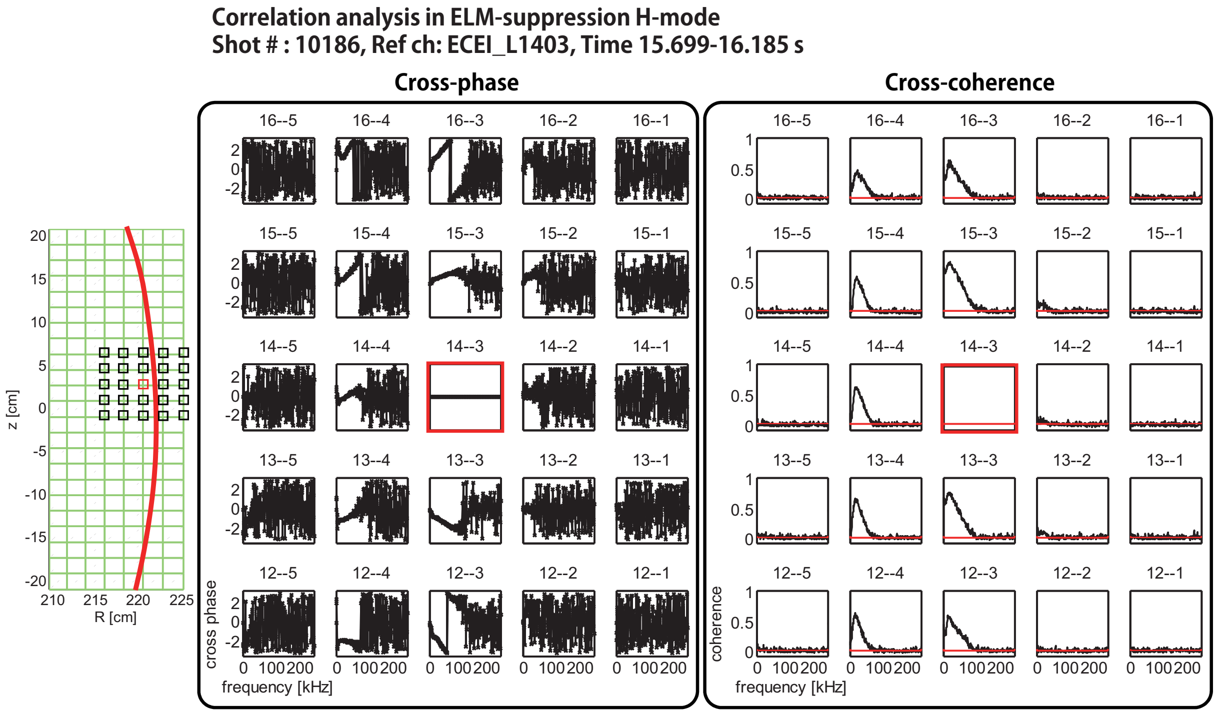

Figure 1: The cross-phase and cross-coherence analysis using 5 (radial) $\times$5 (poloidal) ECEI channels. Strong poloidal correlation inside the separatrix has been observed in range of ≤ 70 kHz during ELM-crash-suppressed phase. The red line is the separatrix position.

between adjacent channels in the direction of major radius R is ~ 2 cm. Therefore, the upper limit of the system wavenumber resolution is $k_\theta \leq 2.25$ cm^{-1} and $k_r \leq 1.5$ cm^{-1} at the edge.

Turbulence measurement in ELM-suppression phase

The correlation analysis has been performed for a steady-state H-mode plasma with ELM-crash-suppressed under $n = 1$ RMP (shot #10186: line-average density $n_{e,l} \sim 2 \times 10^{19}$ m^{-3}, and toroidal velocity ($v_{tor} \sim 70$ km/s). Figure 1 shows the cross-phase and cross-coherence for 5 (radial) $\times$5 (poloidal) channels, which are covering a roughly 10×7 cm at the plasma midplane. The red box represents the reference channel. The correlationa analysis has been performed in time segment ~ 0.15 s which corresponds to ~ 75000 data points for 500 kHz sample rate. The result is then resampled by averaging in unit of 10 segments. An interesting observation in Fig. 1 is the existence of broadband and low frequency coherent mode ($f \leq 70$ kHz) along poloidal direction with narrow radial zone. The high frequency components over 100 kHz are sysmatic noise, characterized by random phase.

The approximate size of turbulent eddies can be estimated using cross-correlation coefficients.

Figure 2 is a zero-delay cross-correlation coefficient, $R_{xy}(\tau=0)$, versus radial and vertical coordinates for turbulent eddies. Gaussian fitting function allows the correlation length to be determined by taking $1/e$ width, $L_{1/e}$: $f(x) = A_1 exp[-x^2/L_{1/e}^2] + A2$, where x is a spatial coordinate, and A_1 and A_2 are amplitude and offset terms that were determined by least square fitting. According to the measurement, the poloidal correlation length is ≤ 1.84 cm and the radial correlation length is ≤ 1.83 cm which are much smaller than typical size of ELM flux tube. Note that the actual size of turbulent eddy could be smaller than the measurement due to the finite resolution of the ECEI system ($R \sim 2.0$ cm, $z_0 \geq 1.4$ cm).

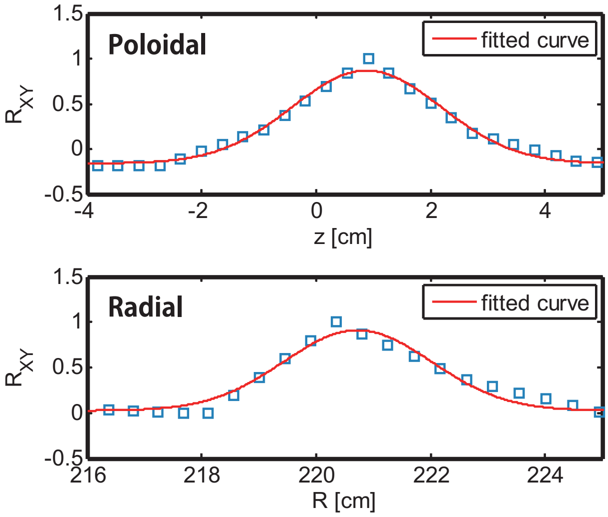

Figure 2: Poloidal and radial size of edge turbulent eddy, estimated from cross-correlation coefficients with zero time lag.

Figure 3 shows the statistical dispersion relation of turbulence in the ELM-crash-suppressed phase represented by local frequency/wavenumber spectrum $S_L(k,f)$ [3]. The $S_L(k,f)$ plot exhibits approximately linear dispersion in a wide range of wavenumbers ($k_\theta \leq 1$ cm^{-1}) and frequencies. This implies that the tubulence in the ELM-crash-suppressied phase has long wavelength and average group velocity of ~ 3 km/s, propagating in the electron diamagnetic drift direction. The measured wavenumber $k_\theta \leq 1$ cm^{-1} gives the characteristic size of turbulence, which is usually compared to the Larmor radius $\rho_s = \sqrt{2m_iT_e}/eB$, here m_i is ion mass, e is electric charge. In this case, $k_\theta\rho_s \sim 0.1$ using $\rho_s \sim 1$ mm at the edge. According to the scale size, possible candidates for the observed turbulence are kinetic ballooning mode (KBM), microtearing mode (MTM), resistive

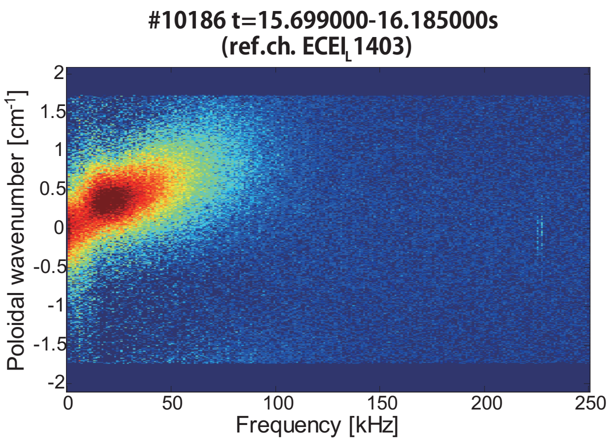

Figure 3: The local frequency/wavenumber spetrum $S_L(k,f)$ during ELM-crash-suppression. The turbulence has long wavelength ($\lambda_{pol} \geq 6$ cm) and average group velocity of ~ 3 km/s in electron diamagnetic drift direction.

ballooning mode (RBM) ($k_\theta \rho_s \sim 0.1$ in tokamak) and ion temperature gradient (ITG) mode ($0.1 \leq k_\theta \rho_s \leq 1$) [4]. However, KBM and ITG can be excluded since they propagate in the ion diamagnetic direction. The remaining candidates, RBM and MTM, can be distinguished by the parity analysis with respect to potential fluctuation which will be measured in future experiment.

Since the KSTAR has equipped with two independent ECEI systems, the parallel wavenumber $k_\parallel$ can also be determined by measuring the phase delay $\Delta\phi_{xy}$ between the two systems according to the relation: $k_\parallel = \Delta\phi_{xy}/\Delta l$, where Δl is the distance between the two toroidally-separated view positions. It is assumed that turbulent eddies are alinged along magnetic field lines and have parallel wavelength large enough to captured by both ECEI systems simultaneously. Figure 4 is a result of parallel wavenumber measurement during ELM-crash-suppressed phase: $2 \leq \lambda_\parallel \leq 8$ m, which is a wide range in reference to the toroidal circumference ~ 14 m of the edge.

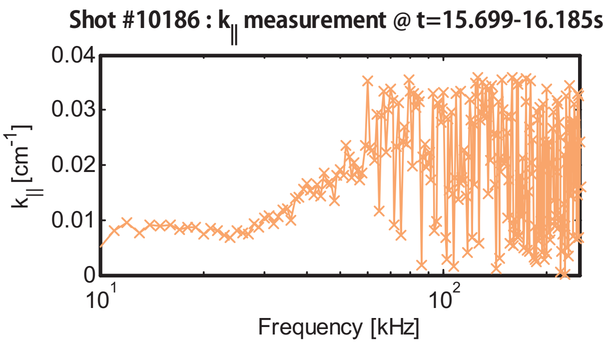

Figure 4: Parallel wavenumber measurement using 3-D ECE imaging technique. The corresponding parallel wavelength range is $2 \leq \lambda_\parallel \leq 8$ m.

Summary

Edge plasma turbulence during the ELM-crash-suppressed period has been studied by employing correlation analysis technique. The result shows clear cross-phase, cross-coherence and $S_L(k, f)$ spectrum in the plasma edge region: poloidal wavenumbers in the range of ≤ 1 cm^{-1}, average group velocity of $\sim$ 3km/s along electron diamagnetic direction, parallel wavelengths in the range of $2 \leq \lambda_\parallel \leq 8$ m. These are unique features of ELM-crash-suppressed phase and may be critical information for understanding the physics of ELM-crash-suppression.

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