EXPERIMENTAL AND NUMERICAL STUDY OF BROAD WAVENUMBER TURBULENCE AND TRANSPORT IN ION INTERNAL TRANSPORT BARRIER PLASMAS ON EAST

[1]P. J. SUN, [2]Y. REN, [1]H. Q. LIU, [1]X. F. HAN, [1]Y. D. LI, [1]G. S. LI, [1]Y. F. WANG, [1]Z. P. LUO, [1]S. X. WANG, [1]T. ZHANG, [1]H. L. ZHAO, [1]H. LIAN, [1]Y. F. JIN, [1]Q. ZANG, [1]G. S. XU, [1]J. S. HU, [1]Y. T. SONG AND THE EAST TEAM

[1]Institute of Plasma Physics, Chinese Academy of Sciences, Hefei, China
[2]Princeton Plasma Physics Laboratory, Princeton, USA

Email: sunpj@ipp.ac.cn

The study of ion internal transport barriers (ITBs) in magnetically confined fusion plasmas is critical for achieving high-performance plasma scenarios. ITBs are localized regions in the plasma core where ion temperature gradients are significantly steeper than in the surrounding regions, leading to improved ion energy confinement, which are essential for sustaining the high temperatures and pressures required for nuclear fusion. ITBs are often associated with the suppression of turbulence and the formation of sheared flows, which act as a transport barrier. The formation and sustainment of ITBs are closely linked to the dynamics of broad wavenumber turbulence, which spans a wide range of spatial scales, from long-wavelength ion-scale turbulence (e.g., ITG modes) to short-wavelength electron-scale turbulence (e.g., ETG modes). Understanding the interplay between broad wavenumber turbulence and transport in ITB plasmas is crucial for optimizing plasma confinement [1-7] and achieving steady-state operation in future fusion reactors such as ITER. In the following, we will present a comprehensive experimental and numerical study of broad wavenumber turbulence and transport in ITB plasmas on EAST, combining advanced diagnostics with state-of-the-art gyrokinetic simulations. Measured by an ordinary mode reflectometer in the steep ion and electron density ITB region, core ion-scale turbulence at $k_\perp < 5\ \mathrm{cm}^{-1}$ (i. e. $k_\perp \rho_s \leq 1.5$, where ρ_s is the ion gyro-radius with sound speed using locally measured T_e, and $k_\perp$ is the perpendicular wavenumber) is found to decrease in the frequency-integrated spectral power S_{tot} as the time evolution for $t = 4.7 - 5.5$ s during the ITB phase [see left panel in Fig. 1]. This indicates that ion-scale turbulence is not completely suppressed during the ion ITB period and that the suppression occurs gradually. Similarly, the electron-scale turbulence power monitored by the CO_2 laser collective scattering diagnostics at wavenumbers $k = 10\ \mathrm{cm}^{-1}$ [see middle panel in Fig. 1] and $k = 20\ \mathrm{cm}^{-1}$ [see right panel in Fig. 1] also continuously decreases over time, following a trend analogous to the evolution of ion-scale turbulence. For both ion-scale and electron-scale turbulence, the overall power remains relatively stable within the time range of $t =$

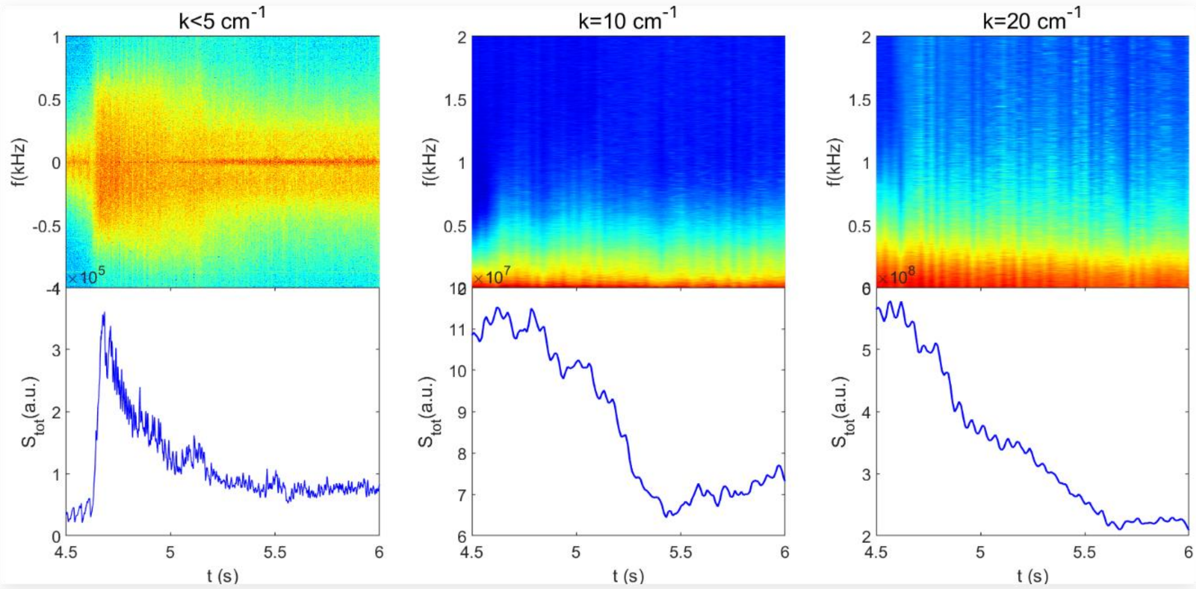

Fig.1: Top panel shows the spectrogram of board wavenumber turbulence with $k < 5\ \mathrm{cm}^{-1}$, $k = 10\ \mathrm{cm}^{-1}$ and $k = 20\ \mathrm{cm}^{-1}$. Bottom panel shows time evolution of these broad wavenumber turbulence power in ion transport barriers plasmas.

5.5 − 6 s, except for a slight increase observed in the turbulence at $k = 10\ cm^{-1}$. This suggests that to further improve plasma parameters under a given heating power, it is necessary to specifically suppress turbulence and transport. This requires us to first identify the types of turbulence and evaluate the potential transport levels driven by the turbulence. TRANSP power balance analysis [see left panel in Fig. 2] indicates that in the region r/a< 0.16, the ion heat transport coefficient decreases to levels below the neoclassical transport level, which is consistent with the formation of the ion internal transport barrier (ITB). However, outside this region, ion heat transport remains anomalous, and the experimentally observed non-negligible ion-scale turbulence is likely the driving mechanism. For electron heat transport, the overall level is higher than the neoclassical transport level, and experimental observations suggest that linearly unstable electron-scale instabilities may be the driving source. Nevertheless, the electron heat transport is generally lower than the ion heat transport, implying that targeted suppression of ion-scale turbulence and ion heat transport could effectively improve plasma energy confinement performance and ion temperature. Middle and right panels in Fig. 2 show the linear stability simulation of ion-scale and electron-scale micro-instabilities using the GS2 gyrokinetic code at around the location of $k < 5\ cm^{-1}$ turbulence monitered in experiment, and the blue horizontal line represents the Waltz-Miller ExB shearing rate. Both ion-scale and electron-scale instabilities are unstable and their linear growth rates are much larger than the Waltz-Miller ExB shearing rate, which is qualitatively consistent with experimental observations of turbulence. Nonlinear simulations are currently underway using the GTC code to further investigate these dynamics. This analysis highlights the importance of identifying and suppressing specific turbulence types to optimize plasma performance in fusion devices.

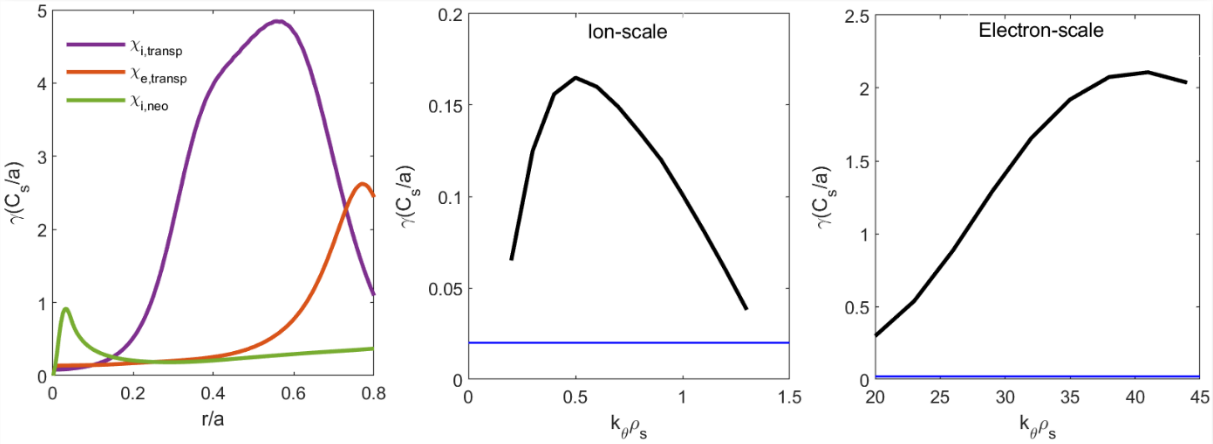

Fig.2: Left panel shows power balance analysis from TRANSP code. Middle and right panels show the linear stability simulation of ion-scale and electron-scale micro-instabilities using the GS2 gyrokinetic code at around the location of $k < 5\ cm^{-1}$ turbulence monitored in experiment, and the blue horizontal line represents the Waltz-Miller ExB shearing rate.

ACKNOWLEDGEMENTS

This work was supported by the Fusion Energy R&D Program of China under Grant Nos. 2024YFE03190002, 2024YFE03190004, the National Natural Science Foundation of China under Grant Nos. 12275316, 12475233.

REFERENCES

[1] Y. REN et al., Phys. Rev. Lett. 106, 165005 (2011).
[2] E. MAZZUCATO et al., Phys. Rev. Lett. 101, 075001 (2008).
[3] W. X. WANG et al., Phys. Rev. Lett. 106, 085001 (2011).
[4] W. X. WANG et al., Phys. Rev. Lett. 87, 055002 (2009).
[5] P. J. SUN et al., Nucl. Fusion 58, 016003 (2018).
[6] P. J. SUN et al., Nucl. Fusion 60, 046016 (2020).
[7] Y. REN et al., Nucl. Fusion 57, 072002 (2017).