DISCOVERY OF CROSS-SCALE NONLINEAR INTERACTION AND BIFURCATION IN MULTI-SCALE TURBULENCE IN LHD PLASMA

[1,2,3]T. TOKUZAWA, [2]T. NASU, [1]D. NISHIMURA, [1]K. IDA, [1]M. YOSHINUMA, [1,2,3]T. KOBAYASHI, [1,3]K. TANAKA, [4]S. INAGAKI, [3]A. FUJISAWA, [1]I. YAMADA, [5]K. ITOH, and LHD Experiment Group

[1]National Institutes of Natural Sciences, National Institute for Fusion Science, Toki, Japan
[2]The Graduate University of Advanced Studies (SOKENDAI), Toki, Japan
[3]Research Institute for Applied Mechanics, Kyushu University, Kasuga, Japan
[4]Institute of Advanced Energy, Kyoto University, Uji, Japan
[5]Chubu University, Kasugai, Japan

Email: tokuzawa@nifs.ac.jp

Here we report, for the first time in the world, an experimental finding on cross-scale nonlinear interactions between fluctuations at ion gyroradius scale (*i*-scale) and electron gyroradius scale (*e*-scale). These findings were obtained by applying a new diagnostic method that simultaneously measures the intensity and anisotropy of turbulent fluctuations. The occurrence of bifurcation events, in which the *i*-scale and *e*-scale turbulence components change abruptly and simultaneously the isotropy of the latter changes, was experimentally observed, qualitatively supports the theoretically predicted description of nonlinear interactions in micro-scale turbulent eddies [1].

In controlled thermonuclear fusion plasma research, the interaction of meso-scale and *i*-scale components as multi-scale turbulence has been actively studied, but in future plasmas that will be heated primarily by alpha particles, the effects of finer scale turbulence such as that of the *e*-scale will become increasingly important. In recent years, the significance of this turbulence interaction between the *i*- and *e*-scales has been pointed out both experimentally and theoretically [2, 3].

In order to study the cross-scale interaction of such *i*- and *e*-scale turbulences, simultaneous measurements at the same spatial location (at the edge region near R = 4.4 m) were carried out by utilizing a microwave Doppler reflectometer [4], which observed *i*-scale turbulence ($k_\perp \rho_s \sim 1.5$), in combination with a millimeter-wave backscattering (BS) system [5], which observed finer *e*-scale turbulence ($k_\perp \rho_s \sim 7.0$). Furthermore, the anisotropy of turbulence in the *e*-scale component was investigated by simultaneous observation of different wavenumber components with the BS receiving antennas newly installed at two different positions in the vacuum vessel.

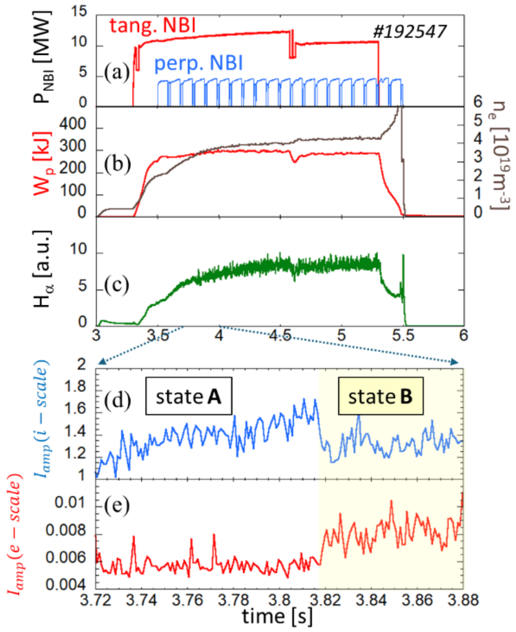

Fig. 1. Temporal behaviors of (a) NBI input power, (b) stored energy (red) and line averaged density (brown), (c) light emission of hydrogen alpha line, (d) ion-scale turbulence intensity, and (e) electron-scale turbulence intensity. State A is before the bifurcation, which occurred around 3.82 seconds, and state B is after the bifurcation.

Discharges with slowly increasing plasma density were used to investigate the onset of bifurcation phenomena and the response of turbulence under LHD conditions that the magnetic axis position in the vacuum field was R_{ax} = 3.55 m and the magnetic field strength was B_t = 1.0 T, as shown in Fig. 1. When the fluctuation of the Hα signal increased around time t = 3.82s, *i*-scale turbulence intensity decreased, and that of the *e*-scale increased rapidly. The temperature and density profiles just before and after the bifurcation into these two states showed almost no significant change at all, especially at the edge region. It should also be noted that this bifurcation of the turbulence states is associated with a change in the property of global evolution of plasmas. The Hα signal, which indicated a loss of energy from the main plasma, showed the transition to a feature like grassy-ELMs at the onset of bifurcation of the turbulence states.

Although the causal relationship here is not yet clear, one might conjecture that the decrease in i-scale turbulence may have caused the increase in e-scale turbulence. In other words, the cross-scale interactions induced the changes in the intensity of i-scale turbulence and that of the e-scale type, which was deformed and suppressed by i-scale turbulent eddies. This hypothesis [6] is further supported by the observation of turbulent anisotropy which was investigated by simultaneously observing the turbulence intensity of wavenumber components of the same magnitude but different directions, as shown in Fig. 2. As in the previous example, the intensity of the e-scale turbulence with two different directional components both increased as the i-scale turbulence decreased around t = 4.27 s. However, the ratio of the intensities due to the observed differences in wavenumber direction changed, with the e-scale turbulence being more isotropic after the bifurcation than before.

Also, we investigate the decorrelation rate of the e-scale turbulence obtained during state A, which is compared with the shearing rate by the i-scale component according to the theoretical model [6]. The decorrelation rate can be estimated to be about 5x10^4 s^{-1}. On the other hand, the estimated electric field produced by the i-scale turbulence eddies is about 0.1- 1 kV/m and its shearing rate is in the order of 10^4 – 10^5 s^{-1}. Thus, the estimated decorrelation rate is well within the range where this dynamic shearing by i-scale turbulence can be effective. This argument is compared to the suppression by a background DC electric field. The i-scale turbulence is considered to be suppressed, when the radial electric field E_r changes and $E_r \times B$ flow shear becomes larger than the decorrelation rate of the i-scale turbulence. However, the effect of this radial electric field on the e-scale turbulence is relatively smaller than in the case of the i-scale turbulence. Therefore, the suppression mechanism by the i-scale component is highly plausible and important for the dynamics of the e-scale component.

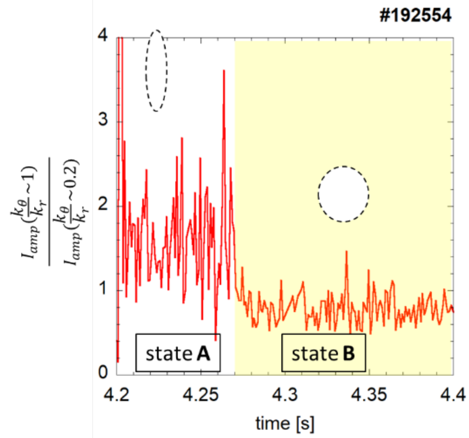

Fig. 2. Time variation of the ratio of the two different wavenumber signal intensities of electron-scale turbulence. The dotted ellipses in the figure are eye guides to the deformation of the electron-scale turbulent eddies. The occurrence of bifurcation mitigates vortex structure change. In this discharge, State A is before the bifurcation, which occurred around 4.27 seconds, and state B is after the bifurcation.

We have succeeded for the first time in the world in simultaneous measurement of i- and e-scale turbulences, as well as simultaneous measurement of the anisotropy of e-scale turbulence at the same spatial location in LHD, and obtained the following results. (i) A bifurcation in the turbulent state occurs between the i-scale oscillations and the e-scale ones. When this bifurcation occurs, the amplitude of the i-scale component decreases, and that of the e-scale increases rapidly. (ii) The change of the anisotropy of the e-scale is observed. Before the bifurcation, the anisotropy of the e-scale component is large (deformed by the i-scale component). After the bifurcation, however, the anisotropy becomes smaller. This turbulent bifurcation qualitatively supports the theoretical depiction [6]. (iii) The decorrelation rate of the e-scale component is observed. The degree of deformation due to a vortex motion of the i-scale component, as evaluated by the commonly-used mixing length model, is found to be as large as or larger than the experimentally-measured decorrelation rate of the e-scale component. The suppression mechanism by the i-scale component is highly plausible and important for the dynamics of the e-scale one. (iv) Thus, the experimental results indicate that it is essential to study cross-scale nonlinear interactions, including i- and e-scale components, to understand the physics of high-temperature nuclear fusion plasmas. This is because further improvements can be expected if this finer-scale (e-scale) turbulence can also be controlled together with i-scale turbulence.

REFERENCES

[1] T. Tokuzawa *et al.*, submitted to Communications Physics.

[2] T. Nasu *et al.,* Proc. 29th IAEA Fusion Energy Conf. (London, 16–21 October 2023) . (available at: https://conferences.iaea.org/event/316/contributions/27815/)

[3] S. Maeyama *et al.*, 2024 Nucl. Fusion **64** 112007 (2024).

[4] R. Soga *et al.*, Journal of Instrumentation **11**, C02009 (2016).

[5] T. Tokuzawa *et al.*, Rev. Sci. Instrum. **92**, 043536 (2021).

[6] S.-I. Itoh and K. Itoh, Plasma Phys. Contr. Fusion **43**, (8) 1055 (2001).