

CONFERENCE PRE-PRINT

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

T. TOKUZAWA

National Institutes of Natural Sciences, National Institute for Fusion Science

Toki, Japan

The Graduate University of Advanced Studies (SOKENDAI)

Toki, Japan

Research Institute for Applied Mechanics, Kyushu University

Kasuga, Japan

Email: tokuzawa@nifs.ac.jp

T. NASU

The Graduate University of Advanced Studies (SOKENDAI)

Toki, Japan

D. NISHIMURA, K. IDA, M. YOSHINUMA, T. KOBAYASHI, K. TANAKA, I. YAMADA

and LHD Experiment Group

National Institutes of Natural Sciences, National Institute for Fusion Science

Toki, Japan

S. INAGAKI

Institute of Advanced Energy, Kyoto University

Uji, Japan

A. FUJISAWA,

Research Institute for Applied Mechanics, Kyushu University

Kasuga, Japan

K. ITOH

Chubu University

Kasugai, Japan

Abstract

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].

1. INTRODUCTION

In controlled thermonuclear fusion plasma research, the interaction of meso-scale and ion gyroradius scale (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 electron gyroradius scale (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 - 25].

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 [26, 27], which observed i -scale turbulence ($k_{\perp}\rho_s \sim 1.5$), in combination with a millimeter-wave backscattering (BS) system [28], 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.

2. EXPERIMENTAL RESULTS IN LHD

Discharges with slowly increasing plasma density were used to investigate the onset of bifurcation phenomena and the response of turbulence under LHD [29] 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 H_{α} signal increased around time $t = 3.82$ s, 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 H_{α} signal, which indicated a loss of energy from the main plasma, showed the transition to a feature like grassy-edge-localized-mode (ELM) [30 -32] 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 [19] 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 [19]. The decorrelation rate can be estimated to be about $5 \times 10^4 \text{ s}^{-1}$. 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 $10^4 - 10^5 \text{ s}^{-1}$. 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.

3. SUMMARY

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 [19]. (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.

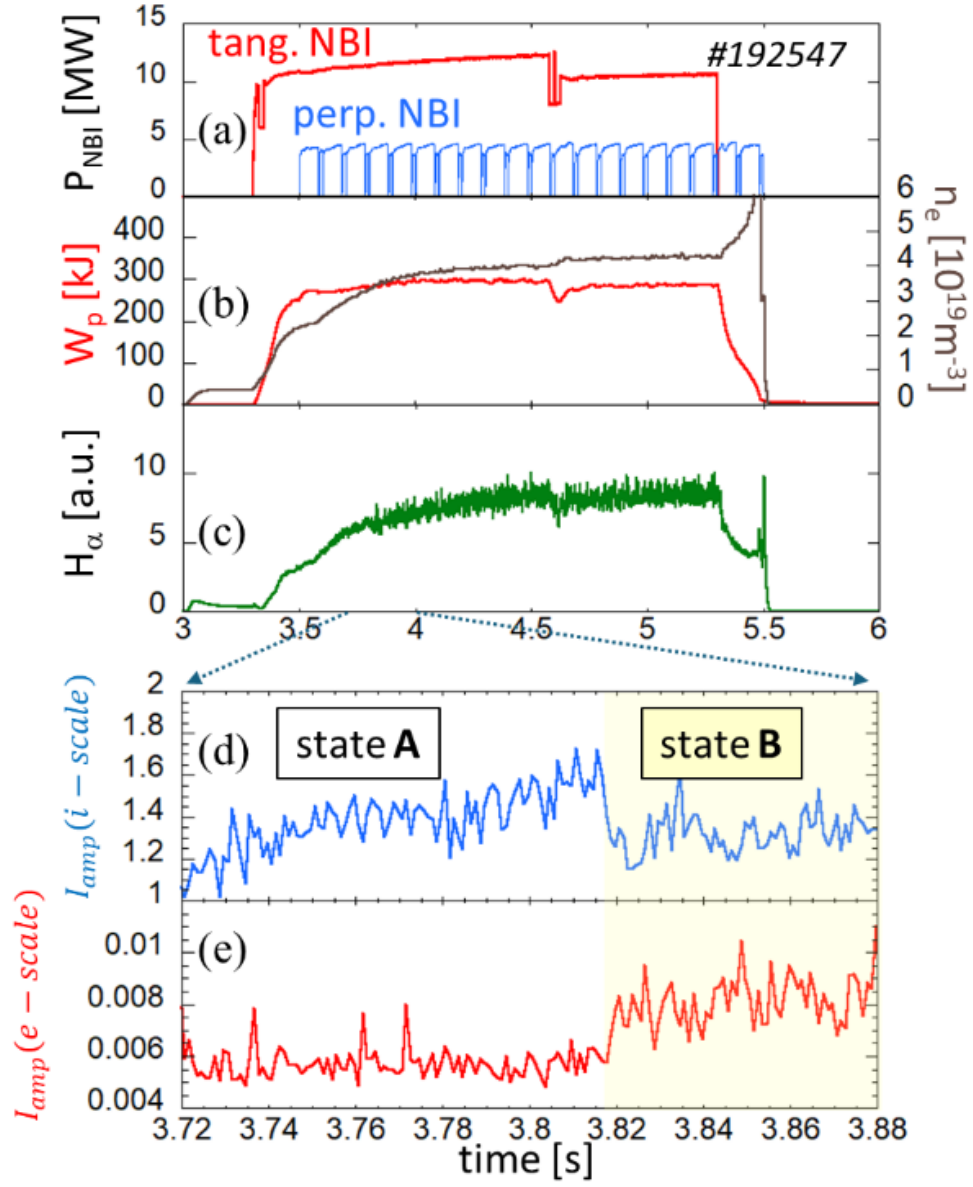


FIG. 1. Temporal behaviors of (a) NBI input power, (b) stored energy (red) and line averaged density (brown), (c) light emission of hydrogen alpha line, (d) ion-scale turbulence intensity, and (e) electron-scale turbulence intensity. State A is before the bifurcation, which occurred around 3.82 seconds,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

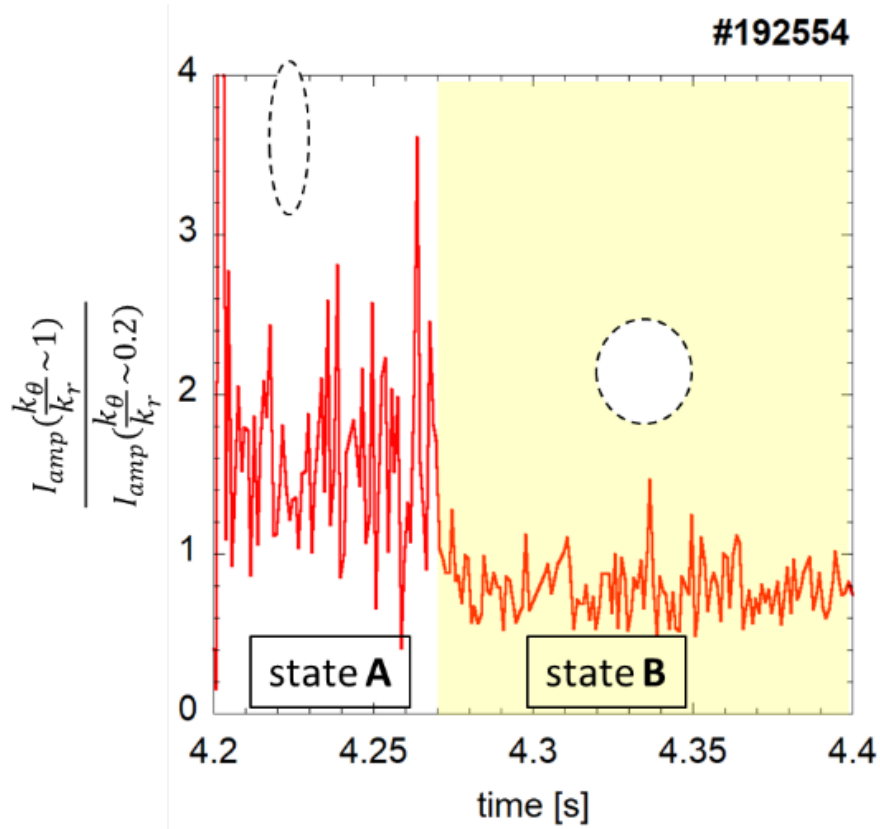


FIG. 2. Time variation of the ratio of the two different wavenumber signal intensities of electron-scale turbulence. The dotted ellipses in the figure are eye guides to the deformation of the electron-scale turbulent eddies. The occurrence of bifurcation mitigates vortex structure change. In this discharge,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

ACKNOWLEDGEMENTS

This study was supported in part by the Japan Society for the Promotion of Science KAKENHI (grant nos. 19H01880, 21H04973, 23H01161, 23K25858, and 24K06997), by a budgetary Grant-in-Aid from the National Institute for Fusion Science (NIFS) LHD project under the auspices of the NIFS Collaboration Research Program, and by the Collaborative Research Programs of the Research Institute for Applied Mechanics, Kyushu University. Additional support was provided by Japan/U.S. Cooperation in Fusion Research and Development.

The raw data were generated at the LHD facility. The data supporting the findings of this study are available in the LHD experiment data repository at <https://doi.org/10.57451/lhd.analyzed-data>.

REFERENCES

- [1] T. Tokuzawa et al., Cross-scale nonlinear interaction and bifurcation in multi-scale turbulence of high-temperature plasmas, *Communications Physics* (in press).
- [2] Nasu, T. et al., Electron-scale turbulence characteristics with varying electron temperature gradient in LHD. *Nucl. Fusion* **64**, 096008 (2024).
- [3] Maeyama, S. et al., Overview of multiscale turbulence studies covering ion-to-electron scales in magnetically confined fusion plasma. *Nucl. Fusion* **64**, 112007 (2024).

- [4] Diamond, P.H., Itoh, K., Itoh, S.-I. and Hahm, T.S., Zonal flows in plasma-a review. *Plasma Phys. Control. Fusion* **47**, R35 (2005).
- [5] Kadomtsev, B.B., *Plasma Turbulence*. (Academic, New York, 1965).
- [6] Ohkawa, T., A transport model for alcator scaling in tokamaks. *Physics Letters A*, **67**, 35-38 (1978).
- [7] Parail, V. V. and Pogutse, O. P., *JETP Letters* **32**, 384 (1980). *Proc. Blh Intl. Conf: on Piasma Physics and Controiiied Nuclear Fusion Rerearch (Brmseh, 1980) vol 1 (Vienna: IAEA) p67*.
- [8] Horton, C.W., Drift waves and transport. *Reviews of Modern Physics* **71**, 735 (1999).
- [9] Sokolov, V. and Sen, A. K., Measurements of Electron Thermal Transport due to Electron Temperature Gradient Modes in a Basic Experiment. *Phys. Rev. Lett.* **107**, 155001 (2011).
- [10] Mattoo, S. K. et al., Experimental Observation of Electron-Temperature-Gradient Turbulence in a Laboratory Plasma. *Phys. Rev. Lett.* **108**, 25507 (2012).
- [11] Moon, C., Toshiro, K. and Hatakeyama, R., Dynamics of Nonlinear Coupling between Electron-Temperature-Gradient Mode and Drift-Wave Mode in Linear Magnetized Plasmas. *Phys. Rev. Lett.* **111**, 115001 (2013).
- [12] Mazzucato, E. et al., Short-Scale Turbulent Fluctuations Driven by the Electron-Temperature Gradient in the National Spherical Torus Experiment. *Phys. Rev. Lett.* **101**, 075001 (2008).
- [13] Ruiz, J.R. et al., Validation of gyrokinetic simulations in NSTX and projections for high-k turbulence measurements in NSTX-U. *Phys. Plasmas* **27**, 122505 (2020).
- [14] Rhodes, T.L. et al., Response of multiscale turbulence to electron cyclotron heating in the DIII-D tokamaka. *Phys. Plasmas* **14**, 056117 (2007).
- [15] Ren, Y. et al., Transport from electron-scale turbulence in toroidal magnetic confinement devices. *Reviews of Modern Plasma Physics*, **8**, 5 (2024).
- [16] Dorland, W., Jenko, F., Kotschenreuther, M. and Rogers, B. N., Electron Temperature Gradient Turbulence. *Phys. Rev. Lett.* **85**, 5579 (2000).
- [17] Idomura, Y., Wakatani, M. and Tokuda, S., Stability of ExB zonal flow in electron temperature gradient driven turbulence. *Phys. Plasmas* **7**, 3551(2000).
- [18] Gao, Z. et al., Temperature gradient driven short wavelength modes in sheared slab plasmas. *Phys. Plasmas* **10**, 2831-2839 (2003).
- [19] Itoh, S.-I. and Itoh, K., Statistical theory and transition in multiple-scale-length turbulence in plasmas. *Plasma Phys. Contr. Fusion* **43**, (8) 1055-1102 (2001).
- [20] Holland, C. and Diamond, P. H., On the dynamics of large-scale structures in electron temperature gradient turbulence. *Phys. Lett. A* **344** 369–82 (2005).
- [21] Maeyama, S. et al., Multi-scale turbulence simulation suggesting improvement of electron heated plasma confinement. *Nature Communications* **13**, 3166 (2022).
- [22] Wagner, F. et al., Regime of Improved Confinement and High Beta in Neutral-Beam-Heated Divertor Discharges of the ASDEX Tokamak. *Phys. Rev. Lett.* **49**, 1408 (1982).
- [23] Biglari, H., Diamond, P. and Hand, Terry P.W., Influence of sheared poloidal rotation on edge turbulence. *Phys. Fluids B* **2**, 1-4 (1990).
- [24] Shesterikov, I. et al., Experimental Evidence for the Intimate Interaction among Sheared Flows, Eddy Structures, Reynolds Stress, and Zonal Flows across a Transition to Improved Confinement. *Phys. Rev. Lett.* **111**, 055006 (2013).
- [25] Carter, T. A., Maggs, J. E., Modifications of turbulence and turbulent transport associated with a bias-induced confinement transition in the Large Plasma Device. *Phys. Plasmas* **16**, 012304 (2009).
- [26] Soga, R. et al., Developments of frequency comb microwave reflectometer for the interchange mode observations in LHD plasma. *Journal of Instrumentation* **11**, C02009 (2016).
- [27] Tokuzawa, T. et al., Ka-band Microwave Frequency Comb Doppler Reflectometer System for the Large Helical Device. *Plasma Fusion Research* **9**, 1402149 (2014).
- [28] Tokuzawa, T. et al., W-band millimeter-wave back-scattering system for high wavenumber turbulence measurements in LHD. *Rev. Sci. Instrum.* **92**, 043536 (2021).
- [29] Takeiri, Y. et al., Extension of the operational regime of the LHD towards a deuterium experiment. *Nucl. Fusion* **57**, 102023 (2017).
- [30] Zohm H., Edge localized modes (ELMs). *Plasma Phys. Control. Fusion* **38** 105 (1996).
- [31] Suttorp, W., The physics of large and small edge localized modes. *Plasma Phys. Control. Fusion* **42** A1 (2000).
- [32] Aiba, N. and Oyama, N., Numerical analysis of key factors for the appearance of grassy ELMs in tokamak plasmas. *Nucl. Fusion* **52** 114002 (2012).