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Mesoscopic transport in KSTAR, HL-3, and DIII-D tokamaks

M.J. Choi[1], J.-M. Kwon[1], P.H. Diamond[2], T.S. Hahm[3], L. Qi[1], Y.U. Nam[1], Y. Lee[3], Y.S. Na[3], M. Jiang[4], Y. Zhang[4], F. Khabahnov[5], and G. McKee[5]

[1] Korea Institute of Fusion Energy, [2] University of California, San Diego, [3] Seoul National University, [4] Southwestern Institute of Physics, [5] University of Wisconsin—Madison

e-mail (speaker): mjchoi@kfe.re.kr

The transport by plasma fluctuations, or simply the turbulence transport, is the biggest obstacle to improving the energy confinement in tokamaks. The conventional framework to understand the turbulence transport is an extension of the classical transport theory in thermodynamic non-equilibrium systems, assuming the linear and local relation between the flux and the spatial gradient of thermodynamic quantities such as Fick's law and Fourier's law. The transport coefficients are estimated by the characteristic spatial and temporal scales of fluctuations and their approximated amplitudes. However, this simplified view of the turbulence transport may not be adequate for some cases, especially in the near-marginal regime [1] where mesoscopic structures emerge due to interactions among plasma fluctuations.

The near-marginal regime is characterized by a mild drive of plasma instabilities around the nonlinear threshold [1]. It would be a spontaneous regime of the self-sustained fusion plasma in future devices, because the turbulence transport sharply increases beyond the threshold, aka the profile stiffness.

Understanding the turbulence transport in the near-marginal regime has been known as a difficult problem. The pioneering theoretical work [2] provided a conceptual framework under the self-organized criticality. Here, the dominant transport mechanism is ballistic transport events, or avalanches, that result from the successive interaction among fluctuations as the flux propagates. The important aspect of transport in avalanching plasmas is a self-similar or scale-invariant behavior. For example, the size distribution of transport events follows a power-law. This means the absence of the characteristic scale. It can have any scale up to the system size. Events of various sizes can occur when a multitude of metastable states exists as in the self-organized criticality system. Physically, this self-similarity or scale-invariance is associated with the joint reflection symmetry, meaning the pair creation of bumps and voids propagating in the down-gradient and up-gradient direction, respectively [2].

In KSTAR tokamak experiments, a ballistic and opposite propagation of electron temperature bumps and voids of various sizes has been observed in the low density and MHD-quiescent L-mode and weakly ITB plasmas with the auxiliary heating [3]. The frequency spectrum of the fluctuation follows a power-law, and the Hurst exponent is larger than 0.5. These characteristics align well with the expectations from the near-marginal transport model, even a catastrophic event.

The global confinement of the avalanche dominant plasmas in the near-marginal regime follows the Bohm or the worse-than-Bohm scaling. Fortunately, a self-consistent gyrokinetic simulation found that avalanches can be limited within a mesoscopic length as the globally ordered zonal flow layers develop [4]. The gyro-Bohm confinement can be recovered with these layers or multiple mesoscopic transport barriers. They are often called the E x B staircase: a pressure profile would be corrugated like a staircase. Indeed, in KSTAR avalanching plasmas the regulation of the avalanche propagation by the E x B staircase has been observed [5].

However, the E x B staircase in KSTAR plasmas is dissipative not stationary, though they persistently reform. More experiments are required to understand the E x B staircase and improve its stability. Recent theory and simulation already provided a hint, beneficial effects of fast ions and impurities. In this talk, a preliminary result of recent experiments in KSTAR, HL-3, and DIII-D to address these issues will be introduced (see Figure 1 for the observations of bumps and voids of various sizes).

References

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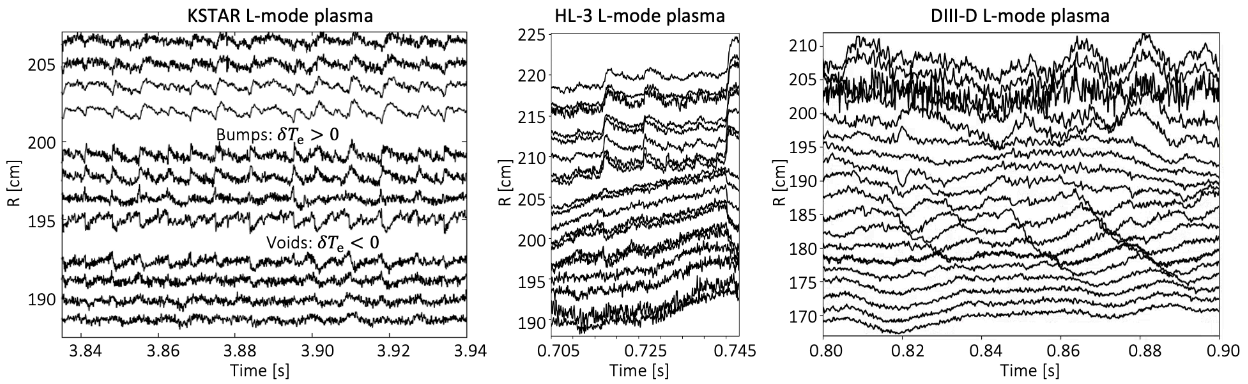

Figure 1. The pair creation and opposite propagation of bumps and voids in KSTAR, HL-3 and DIII-D plasmas