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Role of zonal flow staircase in electron heat avalanches in KSTAR L-mode plasmas

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Understanding the properties of micro turbulence driven transport and the regulation mechanism is critical in magnetic fusion plasmas. The local and quasilinear theory demonstrates diffusive microscopic turbulent transport, which follows the Fick's law relating the transport linearly to the gradient, i.e. Q=-nχ∇T and predicts the gyro-Bohm scaling of transport. However, this conventional localized turbulence and quasilinear calculation of transport fails to address deviations from the expected gyro-Bohm transport scaling observed in tokamak plasmas. To understand the breakdown of Fick's law, non-local and non-diffusive transport mechanism such as avalanching is introduced1. Avalanching is a self-organized criticality (SOC) intrinsic to the systems exhibiting self-similarity, i.e., the spectral power law scaling S(f)~1/f. Here S(f) is the spectral density with f being the frequency. Avalanches are in mesoscopic scale, showing extended and collective fluctuation events, i.e., intermittent bursts.

Avalanches have been commonly observed in various flux-driven fluid and full-f gyrokinetic simulations. Recently, in δf gyrokinetic simulations of collisionless trapped electron turbulence with gKPSP code2, avalanches are observed in electron (ion) heat and particle transport channels. In those simulations, it shows that long stationary and mesoscale zonal flow staircase-like structures can form localized barriers to regulate transport avalanches. The mean zonal flow plays crucial roles in the regulations of avalanching events. Direct measurement of the mean zonal flow global profile is not trivial in experiments, and zonal flow staircase-like structure can only be inferred by the coherence length measurement of the turbulent fluctuations3.

On the other hand, avalanches have been rarely reported in tokamak experiments. This is partially due to the lack of diagnostic tools with sufficient spatio-temporal resolution, and partially due to the difficulty to suppress MHD instabilities which usually dominate the global transport. Recently, an experiment with MHD instabilities suppressed in KSTAR L-mode plasmas reports the non-diffusive avalanche like transport in electron heat channel[4] with a power law scaling S(f)~f^(-0.7). In this experiment, it shows that radial corrugations in the mean electron temperature profile are in a scale Δ~45ρ_i. Zonal flow staircase is believed to be responsible to generate the radial corrugations. There exist evidence from the experiment that implies dynamical interaction between avalanches and global mean flow structures, as shown in Fig. 1. In the figure, it shows before a large scale avalanching event occurs, the transport is regulated and the electron temperature fluctuation radial profile is corrugated. The mean zonal flow shearing could be responsible for this regulations. However, due to the difficulty to measure mean zonal flow from the experiment, regulations of avalanches and formation of radial corrugations in the temperature profile by mesoscale zonal flow shearing cannot be observed directly from experiments. To address this issue, we adopt the gyrokinetic simulations to study this L-mode plasma using gKPSP code[5,6].

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With profiles and configurations from this KSTAR L-mode plasma as inputs, gyrokinetic simulation successfully reproduces the experimental observations. From the simulation, we obtain the power law scaling of electron temperature fluctuations as |δT_e (f)|^2~f^(-0.7) (Fig. 2) and corrugations in the radial profile of mean δT_e with a scale Δ~40ρ_i (Fig. 3), all of which have very good agreement with the experimental measurements. Calculation of the mean zonal flow profile from simulation directly demonstrates the generation of zonal flow staircase and its shearing effects in the regulation of avalanches and temperature corrugations.

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