Experimental observations of the avalanche-like electron heat transport events and their dynamical interaction with the shear flow structure

Minjun J. Choi, Hogun Jhang, Jae-Min Kwon, Jinil Chung, Minho Woo, Lei Qi, Taik-Soo Hahm, Hyeon K. Park, Gunsu S. Yun

1 National Fusion Research Institute, Daejeon 34133, Republic of Korea
2 Seoul National University, Seoul 08826, Republic of Korea
3 Ulsan National Institute of Science and Technology, Ulsan 44919, Republic of Korea
4 Pohang University of Science and Technology, Gyeongbuk 37673, Republic of Korea

Anomalous cross-field transport

The anomalous cross-field transport in tokamak plasmas is still an unresolved problem and turbulence is thought to be responsible for this. Although the prevailing local turbulence theory claims that the turbulence transport is a local diffusive process with a microscopic scale length, there are some experimental observations which cannot be explained by this local picture [1, 2]. While a new model was required for those non-local and non-diffusive phenomena, one model based on the self-organized criticality (SOC) theory was suggested [1]. Avalanches are identified as a dominant transport process in this model and have been found in the many flux-driven numerical simulations [3] and some experiments [4, 5]. In this paper, we report new observations of the avalanche-like event with the joint reflection symmetry (JRS) and its regulation by the self-generated mesoscale shear flow layers. The avalanche-like events were observed in both the NBI heated L-mode and weak ITB plasmas. The L-mode plasma initially had an unstable \( m/n = 2/1 \) tearing mode and it was suppressed using the electron cyclotron resonance heating.

Observation of the avalanche-like transport event in the MHD-quiescent plasma

In the MHD-quiescent periods, the electron temperature \( (T_e) \) fluctuation power increased significantly in the mid radius region \( (r/a \sim 0.35) \) as shown in Fig. 1. Fig. 1(a) shows the \( T_e = (T_e - \langle T_e \rangle) / \langle T_e \rangle \) spectra in MHD-quiescent periods. Both the broadband fluctuation \( (0–75 \text{ kHz}) \) and the narrowband modes (main mode is within the 105–120 kHz band) are found to increase after the tearing mode suppression near \( t = 3.17 \text{ sec} \). The time evolution of their amplitudes is illustrated in Fig. 1(b) with the local \( T_e \) and \( T_i \) gradients.

Before going into details, it should be noted that there is an ambiguity in any fluctuation measurement. The fluctuations in the measured signal can be originated from different sources. For example, the measured \( T_e \) fluctuation can be caused by a displacement and/or a temperature perturbation of an instability, or it can result from a transport event generating heat pulses. It
is not obvious to figure out its origin unless additional information is given. The narrowband fluctuations could be identified as a small scale instability with the $m/n \sim 12/6$ structure. Detailed characterization of the narrowband modes is beyond the scope of this paper, and further investigation is in progress.

On the other hand, the broadband fluctuation was interpreted as a result of the overlapping avalanche-like transport events [6]. This interpretation is based on observations of the fast propagating bumps ($\delta T_e > 0$) and voids ($\delta T_e < 0$) with $m = 0$, the power-law behavior of the event size ($\delta T_e$) power spectrum, and the large Hurst exponent. Note that the frequency of the transport event is the same in any frame, the event size power spectrum (broadband components in 0–75 kHz shown in Figs. 1 and 3) does not require the Doppler shift correction. Then, the RMS amplitude of the broadband fluctuation in Fig. 1 means the strength of transport event activities. More descriptions are given below.

The transport events with a measurable $\delta T_e$ size are identified using the spatio-temporal $T_e$ measurements. Fig. 2 shows observations of the bumps and voids of small and large transport events. The fact that they propagate in the opposite direction from $R = R_{av}$ implies that the flux is invariant under the dual transformations of $x \rightarrow -x \ (x = R - R_{av})$ and $\delta T_e \rightarrow -\delta T_e$ (i.e. the joint reflection symmetry (JRS)) [1]. The propagation speed is about 90 m/s ~ 0.12($\rho_s/C_s$) which is a fraction of the diamagnetic velocity where $\rho_s$ is the sound ion Larmor radius and $C_s$ is the sound speed at $R_{av}$. The large bump propagates down to the plasma boundary, but the small bump propagates over the limited range.

Prevailing power-law spectra and the large Hurst exponent further corroborate the non-diffusive avalanche-like characteristics of the electron heat transport. Fig. 3 shows the measurements of the $\tilde{T}_e$ spectrum at different positions. Pairs of two channels of the electron cyclotron emission imaging diagnostics (ECEI) are used to measure the frequency spectrum accurately by calcu-
Figure 2: The spatio-temporal measurement of the local $T_e$ fluctuation.

Figure 3: (a) The $\tilde{T}_e$ spectra measured at different flux surfaces. (b) The rescaled range statistics for the Hurst exponent estimation in the self-similar range.

Calculating the cross power to reduce the noise contribution. The power-law behavior of the event size ($\delta T_e$) power spectrum reflects the avalanche-like characteristics of the transport events as expected from the self-organized criticality theory [1]. In addition, assuming that spatial scale of the event linearly depends on the event size power, the power-law spectrum in Fig. 3 implies that there is no definite spatial scale for those events (i.e. the spatial criticality [3]). The Hurst exponent ($H$) is also measured using a single ECEI channel near $R_{av}$. The Hurst exponent is a parameter related to the temporal correlation function, and $H > 0.5$ implies the long range temporal correlation or temporal criticality (no definite time scale for those events) [3].

Similar avalanche-like transport events are observed in a plasma with weak ITB [6]. They possess all the important characteristics of the avalanche-like events such as the fast propagation of the bump and void (the JRS), the power-law spectrum, and the large Hurst exponent.
The avalanche-like events in a weak ITB plasma are clearly distinguished from the barrier localized mode often observed in the reversed $q$ ITB plasma as shown in Fig. 4.

**Self-regulation of the large amplitude and long range avalanche-like event**

In the recent numerical simulations, the self-regulation of the avalanche-like events via the formation of the mesoscale $E \times B$ shear flow layers has been observed [7, 8]. Indeed, the mesoscale shear flow layers could be demonstrated in the avalanching plasma by measuring the $T_e$ profile corrugation [6]. Fig. 5 shows $\delta T_e$ images in between the large amplitude and long range avalanche-like events in the L-mode plasma. The jet-like pattern of $\delta T_e$ represents corrugation of $T_e$ profile, which is an evidence of the shear flow layers. The step size of the corrugation is $\sim 45 \rho_i$ where $\rho_i$ is the ion Larmor radius. The large amplitude and long range avalanche-like event is only observed to occur in the period when this corrugation is destroyed. This implies a role of the shear flow layers in the regulation of the avalanche-like event size. More studies to understand the background mechanism of the formation and destruction of the shear flow structure and to assess the avalanche-driven transport quantitatively will be followed [8].

**References**


Figure 4: Irregular bumps from the avalanche-like events versus more regular bumps from the barrier localized mode.

Figure 5: $\delta T_e$ images demonstrating the existence of the temperature profile corrugations with opposite polarities.