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

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Abstract
We present experimental observations suggesting that non-diffusive avalanche-like transport events are a prevalent and universal process in the electron heat transport of tokamak plasmas. They are observed in the low confinement mode and the weak internal transport barrier plasmas in the absence of magnetohydrodynamic instabilities. In addition, the electron temperature profile corrugation, which indicates the existence of the $E \times B$ shear flow layers, is clearly demonstrated as well as their dynamical interaction with the avalanche-like events. The measured width of the profile corrugation is around $45\rho_i$, implying the mesoscale nature of the structure.

Keywords: electron heat transport, avalanche, mesoscale shear flow structure, self-organized criticality

(Some figures may appear in colour only in the online journal)

1. Introduction

Understanding dynamical processes leading to cross-field anomalous transport has been a central issue for more than four decades in magnetic fusion plasma research. Most local turbulence theories [1–3] lead to the gyro-Bohm scaling of transport. Even mesoscale structures can be sheared by the self-generated zonal flows [4] so that the prediction of gyro-Bohm-like transport scaling is quite common from theories and simulations. On the other hand, significant deviations from the gyro-Bohm transport scaling persisted from experimental results [5–7] over the years. To reconcile this discrepancy between the local turbulent transport theory and experimental observations, some non-diffusive transport processes, including turbulence spreading and/or avalanches, have been proposed [8–12]. These non-diffusive transport processes have been observed in many flux-driven fluid [13–17] and gyrokinetic [18–26] simulations. In particular, avalanches are near-ballistic radial transport events of heat accompanied by front propagation of fluctuation intensity, arising from nonlinear critical gradient dynamics. They have been usually referred in relation with the paradigm of self-organized criticality (SOC) [27]. Once generated, they can reach to the edge region about one order of magnitude faster than the usual diffusion time, unless interrupted with a shear flow [11, 13, 15, 18, 22].

Unfortunately, experimental observations of long range avalanches have been rare in tokamak experiments [28, 52]. In addition, the avalanche regulation by the self-generated mesoscale shear flow layers, which was observed in the
recent gyrokinetic simulation [22], has not been demonstrated despite the shear flow layers were identified in turbulence coherence length measurements [29, 30]. This is partly due to the lack of an appropriate diagnostics which can measure temperature variations with a sufficient spatio-temporal resolution. Another practical reason is a difficulty to suppress the magneto hydro dynamics (MHD) instabilities which can dominate the global transport and determine the profiles. In this paper, we show that non-diffusive avalanche-like transport events prevail in the electron heat transport channel in MHD-quiescent tokamak core plasmas using advanced electron temperature ($T_e$) imaging diagnostics [31]. We also provide observations of the dynamical interaction between the avalanche-like events and self-generated mesoscale shear flow layers. The formation of the shear flow layers with a mesoscale width is demonstrated by a direct observation of the $T_e$ profile corrugation.

2. The avalanche-like events in the low confinement mode plasma

We begin our analysis with the KSTAR [32] discharge #13728 which is a limiter low confinement mode (L-mode) plasma with the major radius $R_0 = 1.8$ m, the minor radius $a \sim 0.4$ m, the elongation $\kappa \sim 1.4$, the triangularity $\delta \sim 0.3$, the toroidal field $B_T = 3.0$ T, the plasma current $I_p = 500$ kA, and a monotonic safety factor $q$ profile ($q_{95} \sim 7$ at the 95% normalized poloidal flux). The 4 MW of neutral beam power is applied to heat up the plasma. An $m/n = 2/1$ tearing mode (TM) is shown to be destabilized in the plasma current ramp-up phase. The power spectrogram of magnetic fluctuations measured by a Mirnov coil is shown in figure 1(a). The $\sim 10$ kHz signal shown in figure 1(a) originates from the TM which is stabilized by applying the 1 MW electron cyclotron resonance heating (ECRH). As shown in figure 1(b), the vertical target position of ECRH ($z_{ECRH}$, bold line) and effective deposition widths (black dashed lines). Red dashed horizontal line indicates the expected $q = 2$ surface location ($z_{q=2}$). (c) The total stored energy in the plasma. (d) The electron temperature measurement near $R = 1.95$ m just inside the avalanche initiation position ($R_{av}$). (e)–(g) The average $T_e$, $T_i$, and $V_t$ profiles for periods indicated by arrows of the corresponding colors in (a).

Figure 1. (a) The power spectrogram of magnetic fluctuations. Bottom red dotted lines indicate the $z_{ECRH} \sim z_{q=2}$ period and black dashed line indicates $z_{ECRH} > z_{q=2}$ period. (b) The vertical target position of ECRH ($z_{ECRH}$, bold line) and effective deposition widths (black dashed lines). Red dashed horizontal line indicates the expected $q = 2$ surface location ($z_{q=2}$). (c) The total stored energy in the plasma. (d) The electron temperature measurement near $R = 1.95$ m just inside the avalanche initiation position ($R_{av}$). (e)–(g) The average $T_e$, $T_i$, and $V_t$ profiles for periods indicated by arrows of the corresponding colors in (a).
more investigations, and in this paper we focus on the events observed in the $z_{\text{ECRH}} > z_q = 2$.

A detailed investigation of the $T_e$ fluctuations over a broad radial region suggests that the events are non-diffusive avalanche-like transport processes featuring various radial scales. They are triggered near $R_{av} \sim 1.96 \text{ m}$ which is close to the $q = 2$ flux surface $R_q = 2 \sim 1.95 \text{ m}$. Figure 2 shows the normalized $T_e$ fluctuations ($\tilde{T}_e \equiv (T_e - \langle T_e \rangle)/\langle T_e \rangle$) measured at various radial positions ($y$-axis). $\tilde{T}_e$ is filtered by a 5 kHz low-pass filter and rescaled to be in the $-1$ to $1$ range. Voids ($\delta T_e = T_e - \langle T_e \rangle < 0$) and bumps ($\delta T_e > 0$), propagating inwards and outwards from $R_{av} \sim 1.96 \text{ m}$, respectively, are clearly observed. Vertical dashed lines indicate the long range events whose large heat pulses propagate to the plasma boundary. In addition to these large events, there are also smaller ones highlighted by grey boxes. The smaller heat pulses propagate less than the large ones, implying a different radial transport scale. The propagation speed of a heat pulse can be measured for the large event. It is about $90 \text{ m/s} \sim 0.12 (\frac{v}{a}) C_s$, a fraction of the diamagnetic velocity [35] where $\rho_s$ is the sound Larmor radius and $C_s$ the sound speed at $R_{av}$. Therefore, the escaping time is estimated to be $t_{esc} \sim 5 \text{ msec}$, which is about 10 times shorter than the energy confinement time. In the absence of MHD instabilities, these non-diffusive fast transport events are to be driven by turbulence. One candidate is the heat avalanche which has been proposed as a process for a system to relax perturbations in the context of the self-organized criticality (SOC) paradigm near marginal stability [11, 27]. The pair creation of a void and a bump and their respective upward and downward propagation can be interpreted as the joint reflection symmetry (JRS) which is a property expected in a SOC system [11, 36]. On the profile with a finite mean gradient, the bump (void) will make a net flux down (up) the mean gradient, meaning the existence of preferred transport direction. Then, the flux will be invariant under the dual transformations of $x \rightarrow -x$ and $\delta T \rightarrow -\delta T$, which is called the JRS [36].

A further investigation on characteristics of $T_e$ fluctuations corroborates that the observed events are non-diffusive and avalanche-like and they are the prevalent electron heat transport process in this plasma. Figure 3 shows cross power spectra measured by pairs of two adjacent ECEI channels. In the absence of MHD instabilities, these non-diffusive fast transport events are to be driven by turbulence. One candidate is the heat avalanche which has been proposed as a process for a system to relax perturbations in the context of the self-organized criticality (SOC) paradigm near marginal stability [11, 27]. The pair creation of a void and a bump and their respective upward and downward propagation can be interpreted as the joint reflection symmetry (JRS) which is a property expected in a SOC system [11, 36]. On the profile with a finite mean gradient, the bump (void) will make a net flux down (up) the mean gradient, meaning the existence of preferred transport direction. Then, the flux will be invariant under the dual transformations of $x \rightarrow -x$ and $\delta T \rightarrow -\delta T$, which is called the JRS [36].

A further investigation on characteristics of $T_e$ fluctuations corroborates that the observed events are non-diffusive and avalanche-like and they are the prevalent electron heat transport process in this plasma. Figure 3 shows cross power spectra measured by pairs of adjacent ECEI channels (on the same flux surface) of electron cyclotron emission imaging (ECEI) diagnostics [31]. The incoherent instrumental noise power is greatly suppressed in the cross power spectra by an ensemble
average over \( t = 3.7-4.0 \) s. The cross power spectrum near \( R_{av} \) where the avalanche-like event initiates has the largest fluctuation power with the power-law behavior, \( S(f) \propto f^{-0.7} \), over 0–75 kHz frequency band (black). As moving far from \( R_{av} \) towards the center, the amplitude of the spectrum is reduced while preserving the power-law behavior with an almost identical exponent (grey and light grey). The power-law spectrum of event sizes implies that the transport events can occur in all scales, and rarity of the large size events represents the intrinsically intermittent nature of the large avalanche \[10\].

The power-law spectrum is one of the most fundamental characteristics of a SOC system whose transport is likely to be governed by the avalanching process \[10\]. A small deviation from \(-1\) may result from the finite diffusion processes \[12, 16, 37\]. The prevalent \( f^{-0.7} \) power-law spectra reflect the non-diffusive and avalanche-like characteristics of electron heat transport in this plasma. In accord with the power-law spectra, the Hurst exponent \((H)\) measurement of the \( T_e \) fluctuation near \( R_{av} \) shows a long range temporal correlation \((H \sim 0.73 > 0.5)\) representing a self-similar and persistent characteristics as observed in other avalanching systems \[16, 17, 38, 39, 52\]. The Hurst exponent is calculated using the rescaled range statistics \((R/S)\) \[38\] for the time lag range of \(0.1 < \tau < 1\) ms which corresponds to the frequency range of the power-law spectrum. The Hurst exponent is related to the decay index of a power-law correlation function. The correlation function is an inverse Fourier transform of the frequency spectrum. It also shows the power-law behavior over the corresponding time lag range. The range exhibiting the power-law behavior can be regarded as the self-similarity range and \(0.1 < \tau < 2\) ms was found in JET and TJ-IU edge plasmas \[38\]. \( H > 0.5 \) implies the self-similarity and memory effect (long time correlation, or temporal criticality) which are important characteristics of an avalanching SOC system.

Although an identification of the triggering mechanism for the avalanche-like event is beyond the scope of this paper, there is an indication that \( \nabla T_e \) is likely to be related to activities of the avalanche-like events as observed in the cylindrical plasma \[40\]. We quantify the activities by the root mean square of the cross correlation, i.e. the cross power, between two \( T_e \) signals near \( R_{av} \) to reduce noise contributions. The signals are first filtered by a 1–75 kHz band-pass filter to measure activities of small amplitude events. The 0–1 kHz range is excluded to avoid any possible errors from secular movements of the plasma (10–100 ms time scale). As shown in figure 4(b), a decrease in the small avalanche activities is correlated with the sharp decrease in the local temperature gradient (approximated as \( T_e(R = 1.95) - T_e(R = 1.98) \)) due to large amplitude events. On the other hand, the long range and large amplitude events occur when activities of the small events and the local gradient are frequent and respectively sharp. The detailed process of the large amplitude event will be discussed in section 4 demonstrating an important role of the shear flow layers in avalanche dynamics.

3. The avalanche-like events in a weak internal transport barrier plasma

The prevalence of avalanches can be a universal phenomenon as a confined plasma remains in a marginally stable state \[12\]. This is a way for a magnetized plasma to relax rapidly by expelling accumulated heat in the core from external heating. Indeed, the similar spontaneous avalanche-like electron heat transport event is observed in plasmas with weak internal transport barriers (ITBs), which possibly implies the universality of the avalanche-like event regardless of the plasma stored energy. Figure 5 shows time evolution of some characteristic plasma parameters of the KSTAR discharge \#17245 \[41\]. It is also a limiter plasma with a monotonic \( q \) profile as the aforementioned L-mode discharge but with different \( B_T = 2.7\) T, \( I_p = 600\) kA, and \( q_{95} \sim 5.6\). The 4.5 MW neutral beam (NB) power is injected at \( t = 0.5\) sec, i.e. in the early phase of the discharge to make the ITBs. The total stored energy shown in figure 5(b) increases steadily with the formation of the ITBs. The maximum stored energy is about 390 kJ which is comparable to that of the typical KSTAR H-mode discharge, though the plasma has the L-mode like edge. The sudden decreases of the stored energy at 1.85, 2.0, 3.0, and 4.0sec are due to NB blips which eventually cause the destruction of the ITBs. Figures 5(d)–(f) show the \( T_e, T_i, \) and \( V_t \) profiles indicating the formation of the weak ITBs. Note that the ion and electron ITB foots are slightly different.

During the ITB phase, there is a long period when MHD activities are quiescent. It is this MHD-quietest period that the avalanche-like events are observed. Figure 5(a) shows the power spectrogram of magnetic fluctuations. Except for the unidentified weak 60kHz signal, the spectrogram does not show any noticeable MHD signature. The 30kHz signal in the L-mode phase after the destruction of the ITB is identified as an \( n = 2 \) tearing mode. Figure 5(c) shows the \( T_e \) measurement at \( R = 2.10\) m (\( R_{av} \approx 2.07\) m) where the heat pulses of the avalanche-like events are clearly detected during the MHD-quietest period.

The avalanche-like events found in the MHD-quietest period of the ITB plasma possess all the important characteristics of the L-mode events described in the previous section. They have a fast propagation speed about a fraction of

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Figure 4. (a) The rescaled \( T_e \) at different \( R \). (b) Fast temporal evolution of the \( T_e \) power in the 1–75 kHz frequency band near \( R_{av} \) (black) and the difference of electron temperature across \( R_{av} \) (red).
the diamagnetic velocity \((140 \text{ m/s} \sim 0.18 \left( \frac{\rho_s a}{C_s} \right) C_s)\), the joint reflection symmetry, the long range temporal correlation \(H \sim 0.8 > 0.5\), and the power-law spectrum. \(T_e\) measurements over a broad radial region reveal the ballistic nature of the transport events as shown in figure 6. Again, vertical dashed lines indicate the long range large amplitude events, while some smaller events are highlighted by grey boxes. The propagation speed of heat pulses of the large events can be as high as 140 m/s, and bumps and voids propagate in the opposite direction from \(R_{av}\) exhibiting the JRS. The smaller events propagate over a shorter distance \((\sim 10 \text{ cm})\), and its propagation speed could not be estimated accurately. Interestingly, \(R_{av}\) is also found to be close to the \(R_{q=2}\) position as well as the electron ITB foot position. The Hurst exponent of the \(T_e\) fluctuation near \(R_{av}\) is about \(H \sim 0.8\), and the \(T_e\) fluctuation spectrum shown in figure 7 follows a similar power-law as in the avalanching L-mode plasma. Smaller events are more suppressed in the ITB plasma, which might be related to the existence of the weak internal transport barrier close to the \(R_{av}\). Nonetheless, the heat accumulated inside the transport barrier escapes via the large avalanche-like events. These observations can be interpreted that a common non-diffusive transport mechanism may govern the electron heat transport in the MHD-quiescent L-mode and ITB plasmas. This does

Figure 5. (a) The power spectrogram of magnetic fluctuations, (b) the stored energy, and (c) \(T_e\) measurement near \(R = 2.1\) m. (d)–(f) The average \(T_e\), \(T_i\), and \(V_t\) profiles for periods indicated by arrows of the corresponding colors in (a).

Figure 6. The rescaled \(\tilde{T}_e\) measurements at different radial locations (y-axis). Large avalanche-like events are indicated by dashed lines and small avalanche-like events are highlighted by grey boxes.
not necessarily mean that the electron thermal transport in all ITB plasmas are governed by heat avalanches. Note that all the avalanching ITB plasmas in KSTAR have a monotonic $q$ profile, while the other ITB plasmas often have non-monotonic $q$ profiles with reversed shear in interior [42]. In particular, the barrier localized mode (BLM) is often observed in the reversed shear $q$ ITB plasmas [43, 44]. The BLM-like events are observed also in KSTAR when an ITB forms with a reversed shear $q$ profile. They are clearly distinguished from the avalanche-like events reported in this paper. The symmetry of the large avalanche-like event occurs sporadically without any precursor or crash signature in magnetic or lanche-like events occur sporadically without any precursor or crash signature in magnetic or lanche-like events.

Figure 7. The power spectrum of the $T_e$ fluctuations for the ITB avalanching period (blue), compared with one obtained in the previous L-mode avalanching plasma (black).

4. Dynamical interaction between the avalanche-like events and the mesoscale shear flow structure

Recent studies suggest a hypothesis that the interplay between the avalanche and the self-generated shear flow layers may determine the turbulence transport scaling. It can be Bohm or worse-than-Bohm [23, 45] without the shear flow, while the gyro-Bohm scaling is recovered via a regulation of the avalanche activities by the self-organized mesoscale $E \times B$ shear flow layers [22, 46]. There exist some experimental evidence that the $E \times B$ shear flow layers are present in tokamak plasmas [29, 30]. However, a ubiquitousness of the shear layers, manifested by the temperature profile corrugation [46], and its dynamics have yet to be clearly confirmed in experiments despite some hints in [47].

Interestingly, a careful investigation of the two-dimensional $T_e$ variation in the avalanching L-mode plasma clearly captures the formation and destruction of the $T_e$ profile corrugation. Figure 8(a) shows view frames of the ECEI diagnostics and figure 8(b) is a close-up of figure 2 near $R_{av}$. The ECEI data are filtered by a 3 kHz low-pass filter to reduce the noise while keeping $T_e$ profile dynamics. After a preceding large event, the poloidally symmetric jet-like patterns appear as shown in the frame #1 in figure 8(c) and its vertical cut in (d). The jet-like $\delta T_e$ pattern implies that the $T_e$ profile and $\nabla T_e$ is radially corrugated. Spacing between the local maxima of $|\nabla T_e|$ is roughly 10.8 cm, corresponding to $45\rho_i$ where the ion Larmor radius $\rho_i \sim 0.24$ cm. These symmetric $\delta T_e$ jets are perturbed by a larger scale $m = 1$ perturbation as shown in the frame #2. The large $m = 1$ perturbation has a peak at the top and a valley at the bottom (the $\sin \theta$ behavior). The $\delta T_e$ jets move downwards about $10\rho_i$ within 750 $\mu$s as its spacing expands about $5\rho_i$. If we get into more details, the $\delta T_e$ polarity (from top to center, h3–c2–h2–c1–h1) of the corrugation in the frame #1 and the $m = 1$ perturbation in the frame #2 are correlated with one another, and the opposite polarity (c3–h2–c2–h1–c1) of the corrugation with the $– \sin \theta$ perturbation is also observed. The $m = 1$ perturbation becomes clear in between the frame #2 and #3 as the $\delta T_e$ corrugation becomes blurred in a few milliseconds. The local $T_e$ near $R_{av}$ (and the $\nabla T_e$ across $R_{av}$) increases significantly in the frame #3, and a long range large amplitude event occurs. Inward (outward) propagation of a void (bump) in the $R < R_{av}$ ($R > R_{av}$) region is observed from the frame #4 to #6. The whole process is quasi-cyclic, and the jet-like $\delta T_e$ pattern in #1 forms again after #6.

The long range large amplitude event only occurs after the $T_e$ profile corrugation is destroyed with the appearance of the $m = 1$ perturbation. The $T_e$ profile corrugation reforms in the wake of the large event. This dynamical interaction between the long range avalanche and the shear flow layers is very similar to the observations from the most recent gyrokinetic simulation (GYSELA) study [46], which demonstrates regulated mesoscopic transport events in turbulent plasmas.

It is noteworthy that the measured spacing of the corrugations ($\sim 45\rho_i$) is larger than the measured spacing of the shear layers ($\sim 20–30\rho_i$) reported in [29, 30] from Tore Supra. On the other hand, it is similar with the values reported in the simulation study [46] ($40 \pm 2\rho_i = 40 \pm 2\sqrt{T_e/T_i}\rho_i \approx 42 \pm 2\rho_i$), though the KSTAR plasma parameters are different from the simulation conditions being used there. The nonlinear gyrokinetic simulation using the KSTAR plasma parameters are in progress.

An elucidation of the destruction mechanism of the $T_e$ profile corrugation, though interesting, is beyond the scope of this paper. Note that direct measurements of $E \times B$ shear flow layers were not available due to the lack of a fast flow diagnostics, and the ECEI diagnostics view was not sufficiently large to clearly capture the temperature profile corrugation in the ITB avalanching plasmas.
5. Summary and discussion

In summary, the avalanche-like electron heat transport events are observed in the L-mode and weak ITB tokamak core plasmas when the MHD instabilities are absent. Experimental observations supporting the non-diffusive and avalanche-like characteristics of the transport events are provided. In addition, the existence of the $T_e$ profile corrugation and their dynamical interaction with the avalanche-like events are demonstrated. The measured width of the profile corrugation implies the mesoscale flow structure, limiting the size of avalanche-like events. The long range avalanche-like events occur when the profile corrugation is destroyed.

There are some open issues to be addressed in future works. Firstly, to understand the formation and destruction mechanisms of the $T_e$ profile corrugation and the $E \times B$ shear flow layers, more cross validation researches between experiments and simulations will be necessary. Again, we note the similarity of the spatial scale of the corrugation and shear flow layers from the KSTAR experiment and the recent GYSELA simulation [46]. This may hint a universal underlying physics controlling the mesoscale interaction of avalanches and shear flows, which is independent of detailed quantitative aspects of the plasma conditions or micro-physics. The recent experimental observations [47–49] indicate the proximity of internal minor transport barriers to the rational surfaces, though the simulation finds no correlation between them except the $q = 2$ surface [46]. Secondly, what determines the position of $R_{av}$ where the event initiates is another important problem. In both the L-mode and ITB experiments, $R_{av}$ is close to the $q = 2$ flux surface. A possible role of the rational surface in the avalanche triggering dynamics could be studied further in $q$ scan experiments. Note that some gyrokinetic simulations have reported the roles of rational flux surfaces in the destabilization of the trapped electron mode (TEM) [24] and the enhancement of electron transport at the low order rational flux surfaces [50]. Thirdly, since our study is only limited to the electron thermal transport, it is necessary to investigate other transport channels to compare their dynamics with the electron channel. Multi-field fluctuation measurements employing the various diagnostics (e.g. ECEI [31], microwave imaging reflectometry [51], etc) will be essential. Also, numerical studies such as flux-driven gyrokinetic and gyrofluid simulations will provide a comprehensive physical picture of the multi-channel transport. Meanwhile, it is not very clear how the tokamak plasma which may be regarded as a strongly driven system,
can exhibit the SOC-like dynamics, requiring a very slow perturbation (compared to the relaxation process). A further study is necessary to unveil this conundrum.

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