Final Paper – Phys 235 – 2019 Spring

On Experimental Researches of Avalanches in Magnetic Fusion Energy

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Abstract

Avalanche transport and self-organized criticality (SOC) provide a scheme of how nonlocal transport is fulfilled by interaction between local cells. For magnetic fusion energy (MFE) plasmas, modelling and simulations have shown solid evidence that avalanche events not only exist but also could contribute significantly to the total transport. However, the experimental investigation is still far from sufficient to understand the avalanches in real plasma systems. In this paper, I first review the existing experimental results on this topic. Then I summarize the limitation of them and propose possible direction of solving the problem. Lastly, I give ideas on what can be done beyond the current research scope.

Contents

A. Introduction

In the research of magnetic fusion energy (MFE), transport in perpendicular (to magnetic field lines) direction is a core issue since it's closely related to the confinement of plasmas. The simplest transport mechanism is the Coulomb collision between charged particles, which is determined by the local parameters of the plasma. In addition, there exist a variety of instabilities that can lead to transport in different length and time scales. Normally, the local instability is excited when the characteristic parameter, such as density gradient or temperature gradient, is above a certain threshold (critical value). If transport events caused by the local instability are able to increase the value of the characteristic parameter in the neighborhood above threshold, consecutive excitation will occur. These spatially extended transport events generated by collective excitation are called "avalanches". When avalanches occur, transport is no longer determined locally.

A classic example of the avalanche system is a sandpile, where the slope of the sand (characteristic parameter) determines if the sand falls (instability) down (transport). For a system having the critical slope everywhere, arbitrarily small amount of sand drop at an arbitrary place can excite an avalanche event that runs all the way to the boundary. Such a system is called a "marginally stable" system. In practice, the critical profile is reached by the dynamical equilibrium between inflow (sand drops) and outflow (avalanches) of the sand, thus is close to but normally below the marginality, and has many bumps and voids. Such a profile is called a self-organized critical (SOC) profile. For a SOC system, changing the inflow rate does not changes the profile significantly, since avalanches tend to equilibrate the system toward the marginal stability. However, much higher inflow rate (a "strong" drive) does violate the SOC profile. Hence, the key elements to SOC are:

(1) Disparity in scales: sand particle size (Δ) $\ll$ system size (L). Avalanches occur within the intermediate scale-free range ($\Delta < l < L$), thus exhibit a power-law scaling and self-similarity
(2) Interaction dominated: many degrees-of-freedom that determine the dynamics of the system
(3) Slowly driven: non-existence of a strong drive, thus the threshold matters to the system

Since the various kinds of instabilities resulting in perpendicular transport make plasmas analogous to sandpiles, we expect that the SOC regime also occurs in a plasma system and might be essential to the study of plasma transport. Indeed, people found that the concept of SOC is important to explain the phenomena such as profile stiffness, Bohm scaling of diffusivity, etc. To study this issue, theoretical modelling and simulations based on either simple sandpiles or plasma systems already make much progresses, but the experimental researches still await breakthrough. A review on these researches is given in the review article by T. S. Hahm and Professor Diamond [1]. In this paper, I'll illustrate my opinion on what can be done on the experimental researches of avalanches in the future. Inevitably, I'll first review the progresses that have been done and the problem or limitation of them.

B. Current research progresses

In the following I list the main achievement of the experimental researches so far, and comment on the insufficiency or problem of them.

1. Identification of SOC features

The identification of SOC features is based on the fact that in this regime, transport is dominated by avalanches. This leads to the following characteristics in the observable fluctuations.

(1) Intermittent time series and large Hurst parameter (H):

Avalanche transport is intermittent. The intermittent time series exhibit persistence of the fluctuation level (long-term memory) and appearance of large events. For example, the signal in Figure 1(a) is an intermittent signal while Figure 1(b) is not.

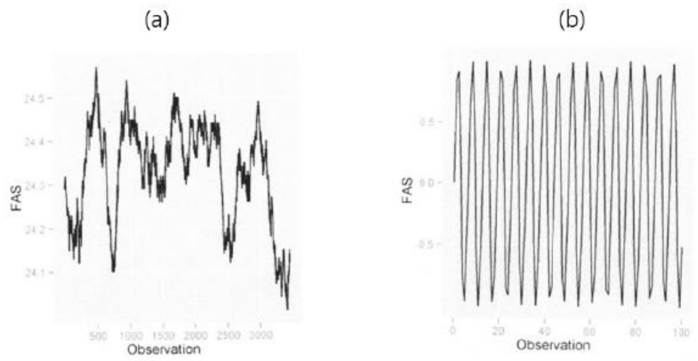


Figure 1. Signals (a) with and (b) without long-term memory [2]

The persistence in fluctuation level also implies algebraic decaying tail in the auto-correlation function of the signal. But in practice, a better way to evaluate the intermittency of a time series is calculating the Hurst parameter (*H*), which is most convenient from the R/S (range/standard deviation) analysis. For an intermittent signal, the calculated H should be $0.5 < \mathrm{H} < 1$.

For experiments in the core plasma, the electron temperature fluctuations (δT_e) measured by electron cyclotron emission (ECE) in DIII-D tokamak exhibited $\mathrm{H}{\sim}0.66 - 0.82$ in a MHD-quiet regime [3]. Further investigation using MHD-quiet L-mode regime revealed $\mathrm{H}{\sim}0.8$ for δT_e and $\mathrm{H}{\sim}0.6$ for δn_e [4], both showing decreasing *H* with increasing minor radius. Similar measurement on KSTAR tokamak also showed $\mathrm{H}{\sim}0.75$ for δT_e [5].

For experiments in the edge plasmas, autocorrelation function of ion saturation current in W7-AS clearly showed algebraic tails [5] (Figure 2(a)). Data analysis gave $\mathrm{H}{\sim}0.62 - 0.72$ in the electrostatic fluctuations of the edge plasma in various types of confinement plasmas such as tokamaks [5]. Electrostatic fluctuations in the TEXTOR tokamak showed *H* decreases from ~0.8 inside the last closed flux surface (LCFS) to ~0.6 in the scrape-off layer (SOL) [6], shown by the black circles in Figure 2(b).

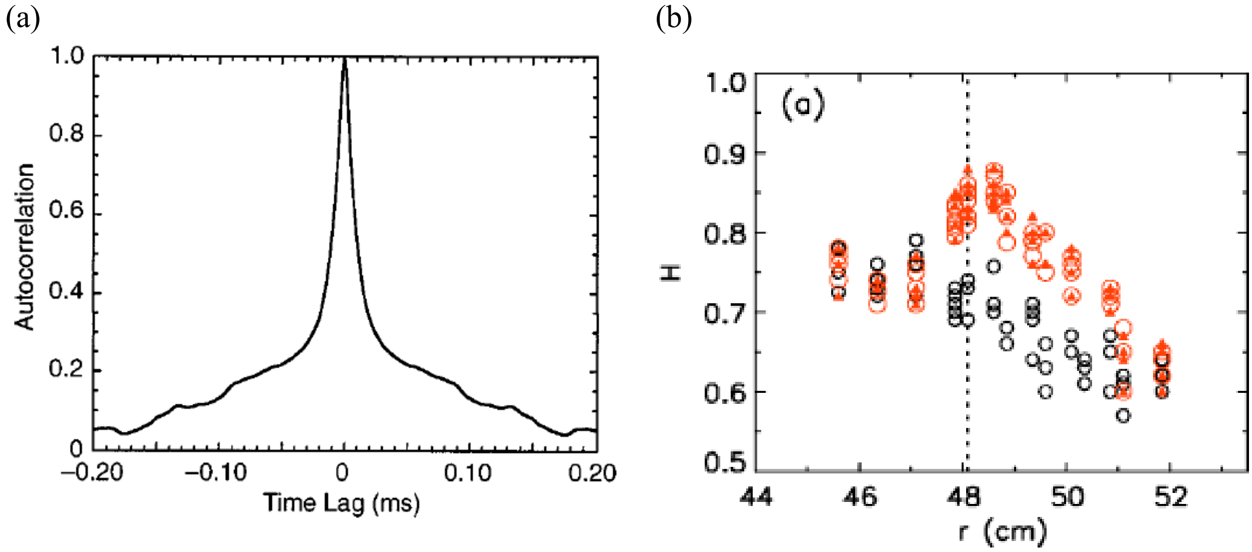


Figure 2. Intermittency of the fluctuations in edge plasmas (a) autocorrelation function of ion saturation current fluctuations in W7-AS [5] (b) radial dependence of *H* in TEXTOR (black circles) [5]. Dashed line: LCFS

All of these experiment results showed Hurst parameter well above 0.5, which indicated intermittent nature of the fluctuations. Moreover, they all pointed out that H decreases with increasing minor radius r. However, we notice that the results in core plasmas were poor in spatial resolution due to the limitation of the diagnostics. Furthermore, the measurement for ion temperature fluctuation is still absent.

(2) Radial propagation and join-reflection symmetry (JRS):

Naively, since avalanche events propagate downhills, we expect to identify avalanches by the propagation of fluctuations in radial direction. Moreover, avalanches are scale-free, thus we can distinguish them as radial motion of fluctuations ranging in a wide variety of length scales. The modelling and simulational results in Figure 3 show the typical out-going patterns.

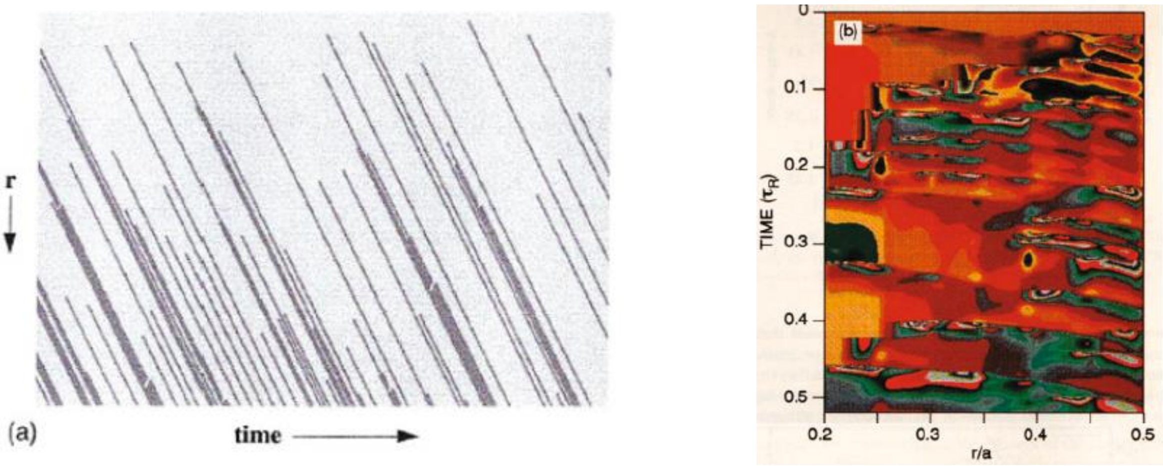


Figure 3. Radial propagation of avalanches in (a) overturning of a sandpile model [7] (b) pressure fluctuations in plasma simulation [8]

However, further investigation into the hydrodynamical model of avalanches showed the property of "joint-reflection symmetry" (JRS), which simply stated that blobs go downhills and voids go uphill. This property is conceptually illustrated in Figure 4(a) and confirmed in simulation in Figure 4(b).

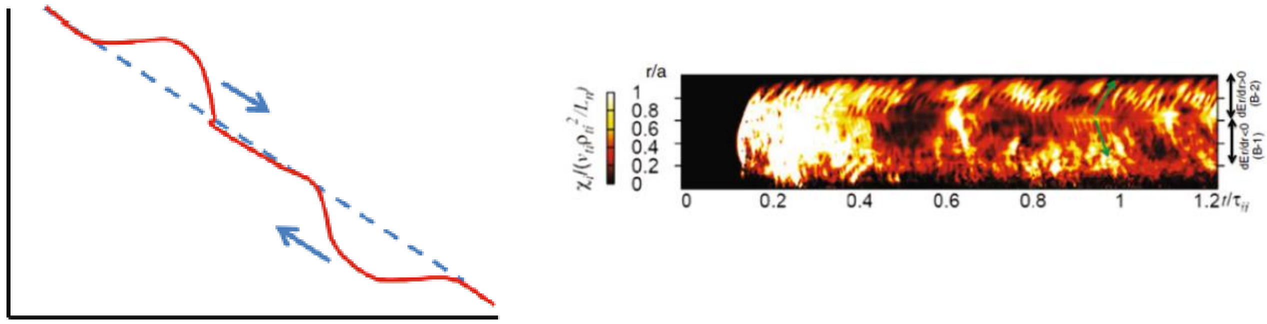


Figure 4. JRS (a) Cartoon [1] and (b) simulation results from gyrokinetic simulation of plasmas [9]

Experimental results in core plasmas also showed the avalanche-like radial propagation events such as Figure 5(a) from DIII-D [4], and the feature of JRS such as Figure 5(b) from KSTAR [5]. The radial velocity was found ~0.1 the diamagnetic velocity. Note that the avalanche events didn't have a specific radial length scale. However, the radial resolution of the ECE measurement was not high enough to resolve events in a wider range of length scale.

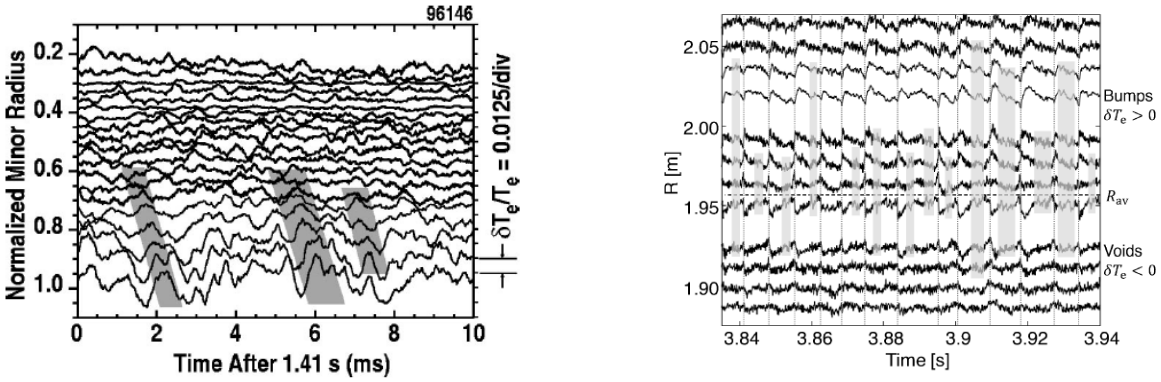


Figure 5. (a) Avalanche-like radial propagation in DIII-D [4] and (b) features of JRS in KSTAR [5].

For the edge plasma experiments, there are a wider variety of diagnostics to provide spatial resolution of fluctuations. The images of outward propagating blobs were captured by gas-puff measurement in Alcator C-Mod tokamak [10]. The image of an outward propagating bump and an inward propagating void (less obvious) was captured by beam-emission spectroscopy (BES) near the LCFS in DIII-D [11], as shown in Figure 6(a). In NSTX [12], Langmuir probe measurement found larger population of density voids inside the LCFS, while more peaks outside of it, as shown in Figure 6(b). It was also found that the radial velocity was inward inside LCFS and outward outside, well consistent with JRS. However, statistical information on the radial length scale of these structures are still absent.

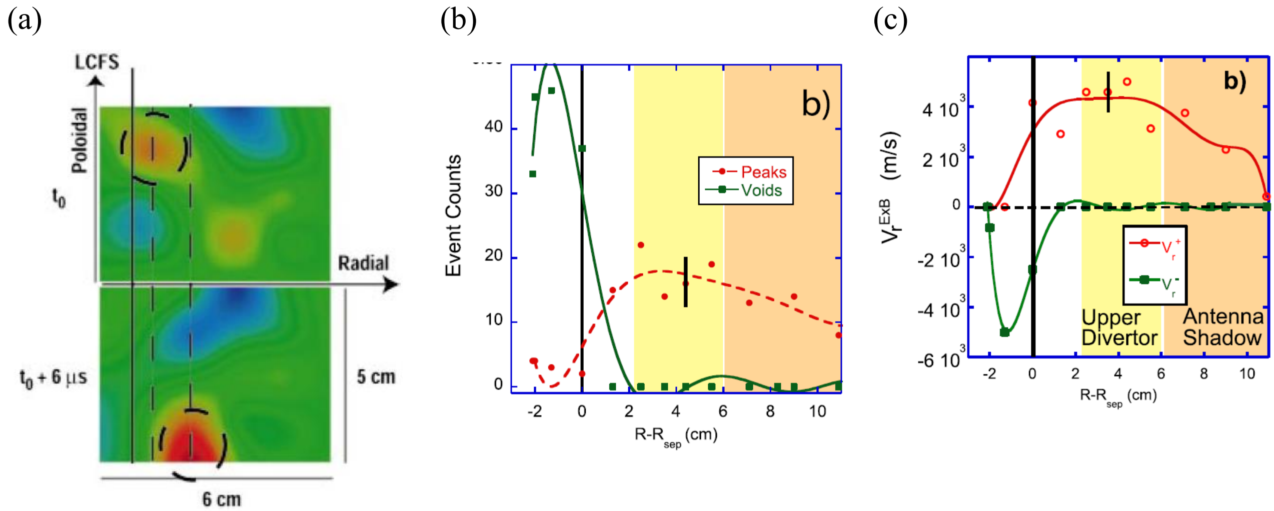


Figure 6. Evidence of radial transport near LCFS. (a) density fluctuation in DIII-D [11] (b) peaks/voids population of density fluctuations and (c) radial velocity in NSTX [12].

(3) Three-stage power spectrum

The three-stage power spectrum is an important characteristic for a SOC system, where a lowest frequency $\sim f^0$ region reflects occasion of the large events, a higher frequency $\sim 1/f$ region targets the $H\sim 1$ intermittency, and the highest frequency $\sim 1/f^4$ region captures the underlying microscopic mechanism. Such features of the power spectrum were already shown in a sandpile modelling [7] (Figure 7(a)). Plasma simulations [13] (Figure 7(b)) and gyrokinetic simulations [9] (Figure 7(c)) also succeeded in reproducing such spectrum.

(a) (b) (c)

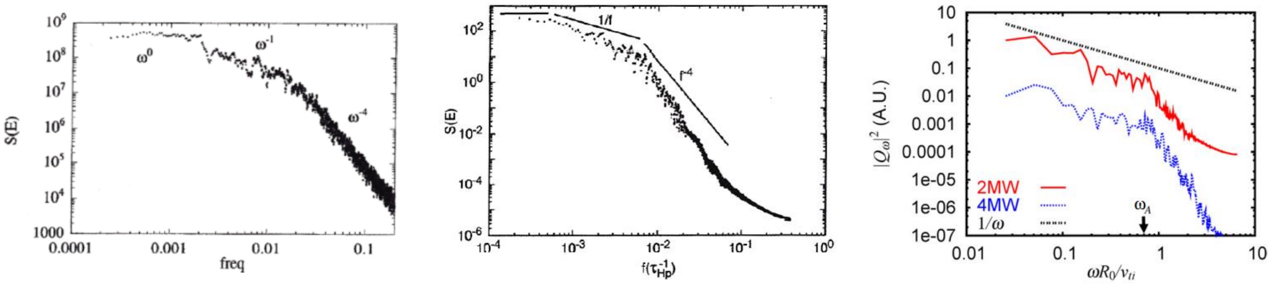


Figure 7. Three-stage power spectrum found in (a) sandpile modelling [7], (b) plasma simulation [13] and (c) gyrokinetic plasma simulation [9].

Despite the success in modelling and simulations, the experimental frequency spectra were often limited by the finite temporal resolution or the short discharge period, which respectively made the characterization of the high-frequency and low-frequency range difficult. Moreover, activities other than avalanches, such as MHD modes, other electrostatic waves or simply instrumental noises might also influence the spectra. As a result, normally only the $\sim 1/f$ regime was clearly identified.

For the core plasma, ECE signals in DIII-D [3] showed clearly the $\sim 1/f$ region, while the high frequency feature was disguised by the instrumental noises (Figure 8(a)). ECE measurement in KSTAR [14] also exhibited a $f^{-0.7}$ dependence (Figure 8(b)). The quantitative difference in the power still awaits systematic investigation. Nevertheless, increasing the signal-to-noise ratio is still the main issue.

(a) (b)

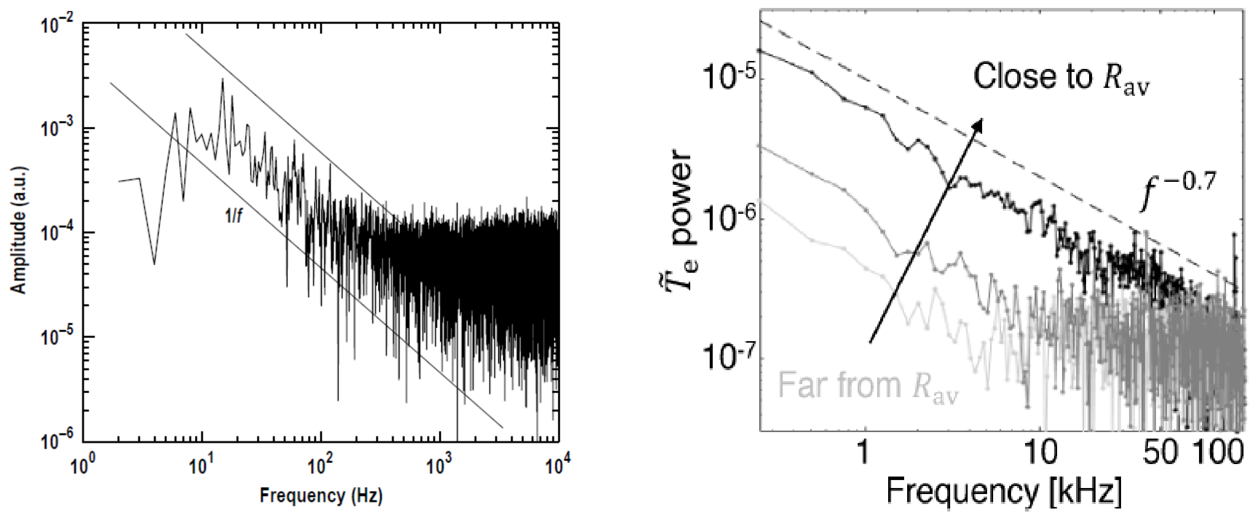


Figure 8. Power spectra of ECE signals in the core plasma of (a) DIII-D and (b) KSTAR.

For the edge plasma and SOL, Langmuir probe measurement offered spectra in wider range of frequency. Ion saturation current fluctuations (~ density fluctuations) spectrum in edge plasma of W7-AS [5] showed clearly the three-stage feature (Figure 9(a)). Gas-puff imaging spectra in Alcator C-Mod resembled that of the Langmuir probe [10], which exhibited the first two stages (Figure 9(b)). Floating potential fluctuations in TEXTOR [6] also showed the three-stage feature (Figure 9(c)). However, power spectrum of temperature fluctuations is absent.

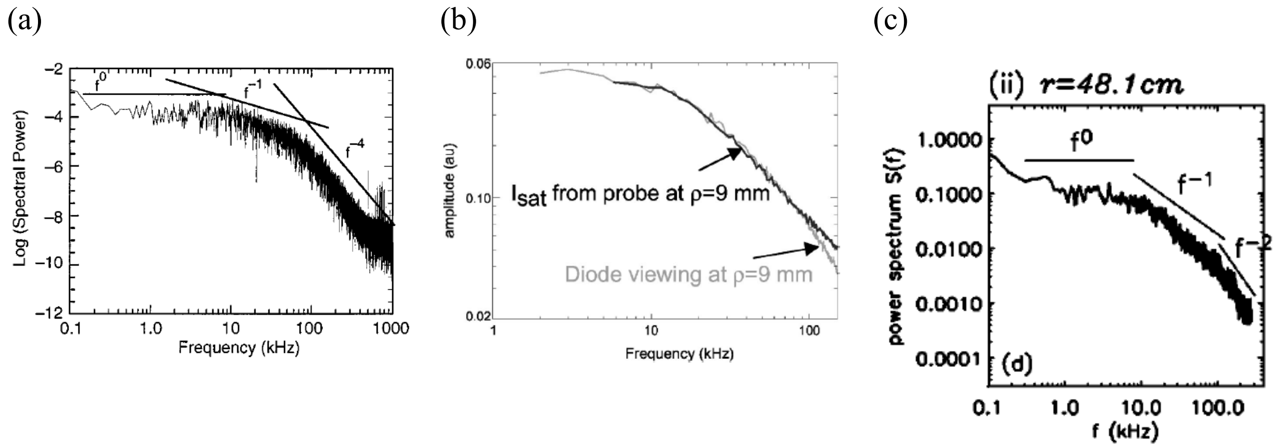


Figure 9. Power spectra of the edge plasmas (a) ion saturation current in W7-AS [5] (b) ion saturation current and gas-puff imaging emission in Alcator C-Mod [10] (c) floating potential in TEXTOR [6]

(4) Thick tails in PDF of fluctuation strength

In contrast to the Gaussian distribution from non-intermittent processes. The intermittency nature of avalanches implies a fat tail in the probability distribution function (PDF) of fluctuation strength. The large value of higher moments of PDF such as skewness can also reflect this feature. In terms of transport, it suggests that a large portion of the total heat flux is carried by the large events.

Gyrokinetic simulation results clearly showed these features. For example, a gyrokinetic simulation showed a ~0.4-0.5 fraction of the total heat flux was carried by the large events [15] (Figure 10(a)). Similar simulation [16] gave further statistical information showing that while the heat flux had more large event propagating outward (Figure 10(b)), the PDF in drift velocity (momentum) fluctuation was more isotropic (Figure 10(c)).

(a) (b) (c)

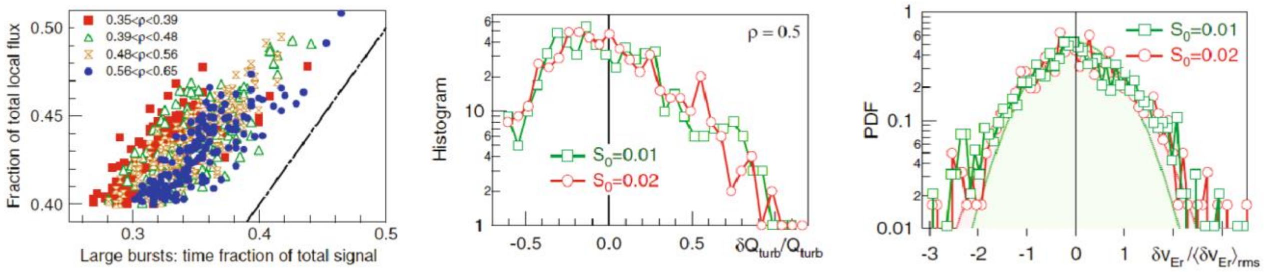


Figure 10. Gyrokinetic simulation results of (a) fraction of total heat flux carried by large events at different radial location (b) histogram of turbulent heat flux [16] (c) PDF of drift velocity [16]

As for the experimental results, while the non-zero skewness of BES density fluctuations in DIII-D [11] (Figure 11(a)) and electrostatic fluctuations and particle flux in NSTX [12] (Figure 11(b)) clearly showed non-Gaussian features for the edge plasma, the PDF data were not available. Moreover, the experimental data of heat flux distribution is still absent, making it difficult to address this issue.

(a) (b)

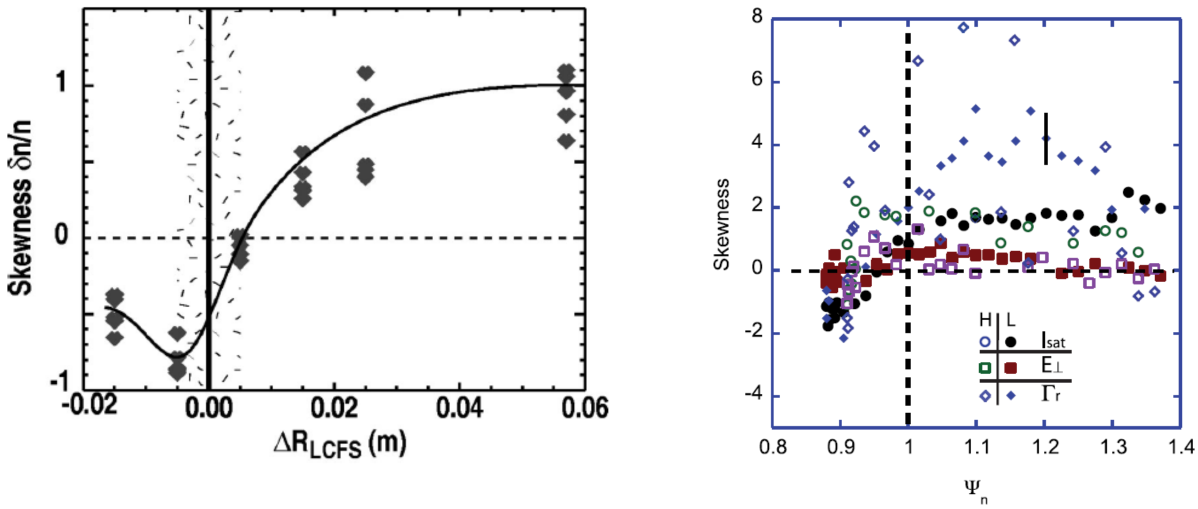


Figure 11. Skewness of fluctuations in edge plasma (a) BES density fluctuations in DIII-D [11] (b) electrostatic fluctuations and particle flux in NSTX [12].

2. Response to a shear layer

An important approach to control the avalanches is applying a shear flow. The sandpile model [8] showed that a sheared layer was able to decrease the long-range correlation of the fluctuations, suppress the low-frequency fluctuating power while increasing the high-frequency one, and decrease the total diffusivity of the SOC system (Figure 12).

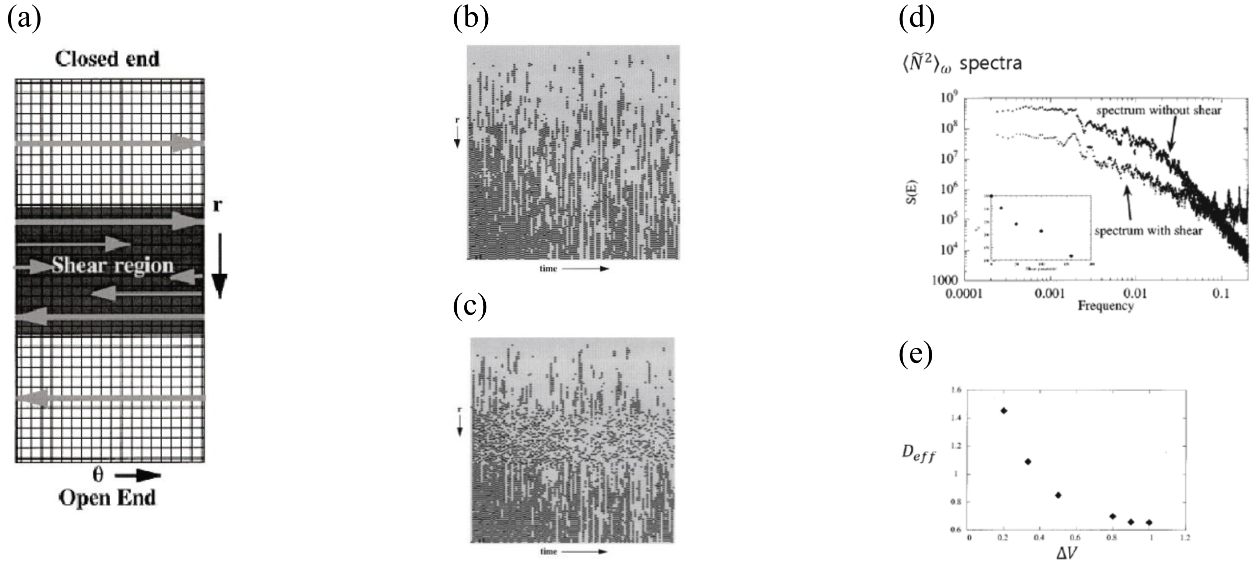


Figure 12. Analysis for a sandpile system with sheared flow layer [8] (a) setup of the system (b) overturning patterns without shear (c) with shear (d) power spectrum and (e) dependence of diffusivity on the maximum velocity

An attempt to carry the sheared-flow experiment was conducted in the edge plasma of TEXTOR [6] (Figure 13). While the spectra did show the suppression in the power of the low-frequency events, the non-vanishing autocorrelation in the longest time lag was in contrast with the idea that the avalanche correlation length would be suppressed. Moreover, the increased Hurst parameter showed that intermittency was not suppressed by the flow shear. Therefore, more experiments and further investigation are needed on this issue.

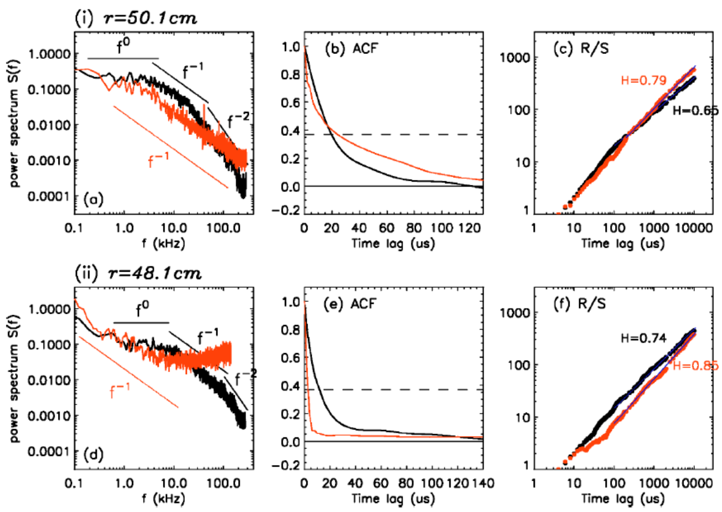


Figure 13. The power spectrum, auto-correlation function and R/S analysis for Hurst parameter in the edge plasma of TEXTOR with (red) and without (black) flow shear at locations (i) outside of (ii) inside the shear layer [6].

3. Avalanches in different operating regimes

Whether to address the underlying mechanism for avalanches in plasmas or to study the influence of avalanches to the confinement, comparison between avalanche features in different operating regimes is an important study. However, a systematic study is still absent.

For the edge plasma, comparison between fluctuations in L-mode and H-mode in DIII-D showed that intermittent pulses in signals had larger amplitude in the L-mode than in the H-mode [11], indicating a higher intermittency in L-mode. An L-H transition experiment in NSTX [12] also found sharp drop in the fluctuation level of the plasma blobs (Figure 15(b)(c)), while slight decrease might be identified in the event count of intermittent transport and the radial size of the blobs (Figure 15(a)(d)). These might help us to understand the lower confinement in L-mode. Nevertheless, a systematic study of changing operational parameters based on steady-state analysis might be better to understand the mechanism of the underlying SOC system.

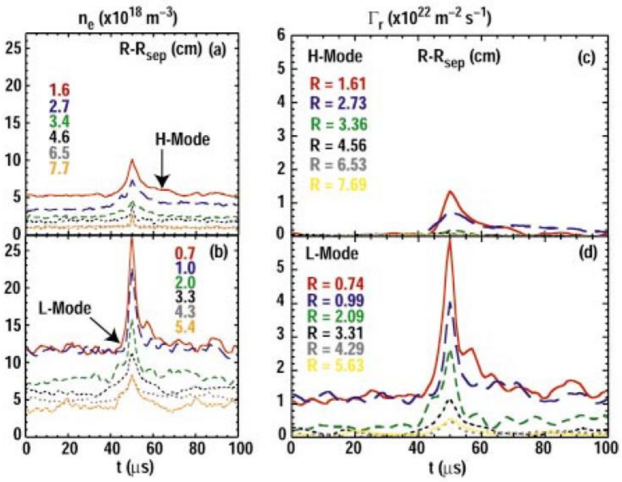


Figure 14. Intermittent transport events in density and radial flux in L-mode and H-mode of DIII-D [11].

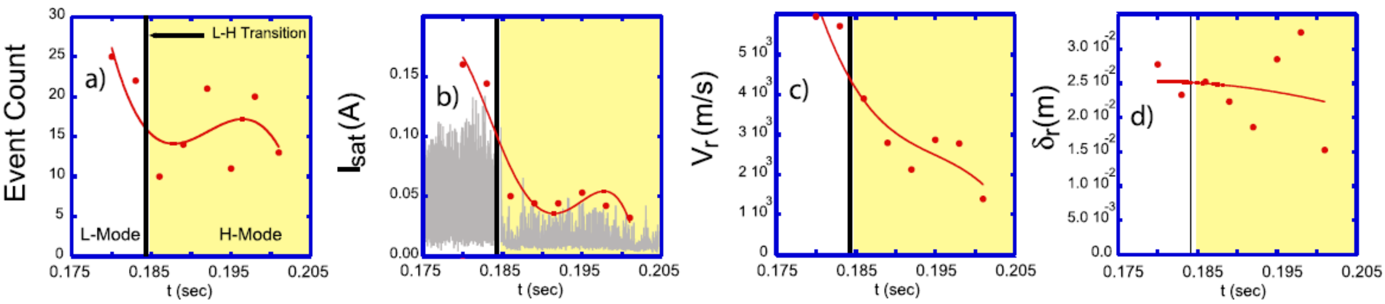


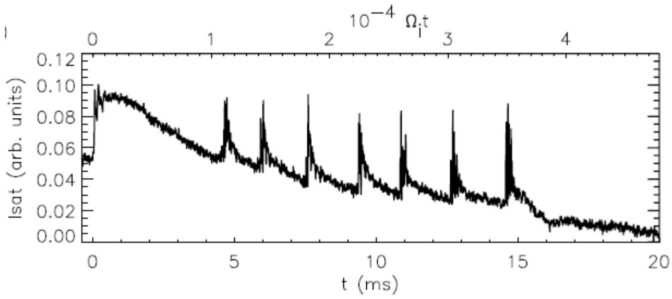
Figure 15. Change of the characteristic of plasma blobs upon L-H transition in NSTX [12].

4. Identification of avalanches in linear devices

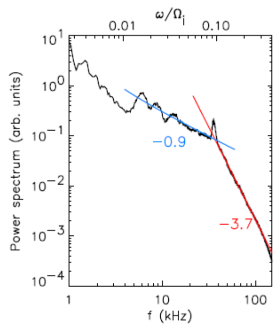
So far, I've only shown the experimental results in confinement devices such as tokamaks. The linear devices designed for basic plasma experiments actually offered very little chance to study this issue currently, mainly due to the low contrast between "sand size" and the "system size". However, the linear devices provide simpler geometry and thus simpler system for underlying instabilities. Hence, they in principle can give more robust results on the analysis of avalanche events, if available.

An attempt to look for avalanches in a linear device was carried on LAPD [17]. The decaying plasma was heated on a certain radial position, generating large fluctuation events propagating outward. Although the time series did show very large events (Figure 16(a)) propagating outward (Figure 16(c)(d)), the highly periodic behavior gave rise to the question that if it was simply some large wave packet. Further analysis on statistical features like the Hurst parameter, the PDF of fluctuations, and the radial size of the events might be necessary. However, the power spectrum well reproduced the $\sim 1/f$ and the $\sim 1/f^{-4}$ regimes. If the giant fluctuation event was not generated by avalanches, we should ask if the three-stage spectrum is a unique feature of avalanches, or of a broader concept. This also gives rise to the question that how we can characterize avalanches if a larger global fluctuation is present.

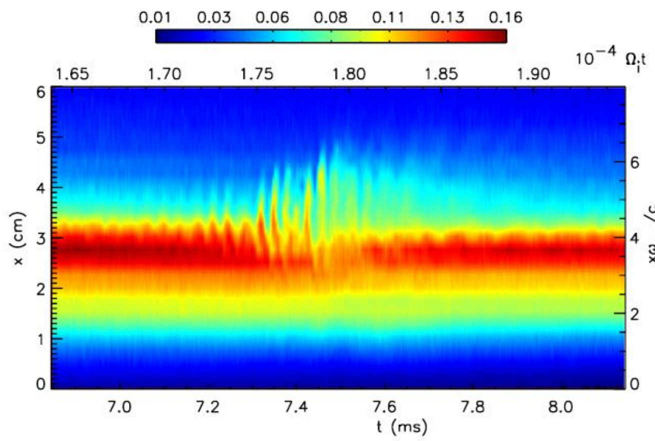
(a)



(b)



(c)



(d)

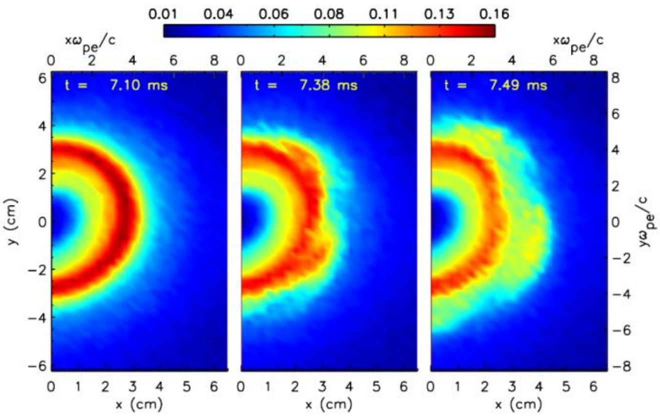


Figure 16. Ion saturation current signals showing the large fluctuation events in LAPD [17] (a) time series (b) power spectrum (c) time change of radial profile (d) snapshots of the 2D profile.

C. Limitation of current work and possible solution

In this part, I summarize the limitation of the current experimental work. Some of them have been described in the previous chapter.

1. Insufficient diagnostic methods

One of the major problems of current measurement is the insufficiency of existing diagnostic approaches. This issue, however, doesn't have a quick solution. I point out the major insufficiency in the following.

(1) Spatial and temporal resolution

The scale-free nature of avalanche events makes them hard to fully characterized in experiments. Temporally, larger events need longer discharge time to detect, while fast small events might be strongly influenced by instrumental noises, as we've seen in the ECE measurement. The former issue might be compensated by taking ensemble average, while the latter needs increasing the signal-to-noise ratio. Spatially, the robust traditional measurements like Langmuir probes cannot resolve fine scale structure, while the physical meaning of new imaging diagnostics like gas-puff imaging is not easy to see.

(2) Unavailable measurement

While ion temperature gradient is an important instability source and ions can efficiently carry heat, the fluctuation of ion temperature is not available yet. Another challenge is the measurement of the local heat flux, which requires the information of density, temperature and velocity at the same time. In theory and simulations, the large tail in PDF, the join-reflection symmetry and the asymmetry between outward and inward propagation of heat flux are important results. Heat flux fluctuation in experiment is strongly required. Obviously, measuring n, T and v simultaneously at one location is not possible in experiments. Correlation-based analysis might solve the problem but needs similar spatial and temporal resolution for these measurements. Note that the current velocity measurement is mostly based on potential measurement. A direct velocity measurement such as Mach probes might give more solid results.

For the core plasma, the situation is worse than the edge plasma, since few diagnostic approaches are available here, and the existing diagnostic like ECE suffers noises and poor spatial resolution. These issues await technological breakthrough.

2. No information on parameters of underlying model of SOC

The concept of avalanches and SOC can be well described by the sandpile model. The experiments have also searched for the clue of existence of underlying sandpile by showing the characteristic of observables. However, if a corresponding sandpile for a given system really exists, we should be able to determine the fundamental parameters such as the size of "sand particles" (cells), the threshold of the instability, and the toppling rules. Once having such information, it is easier to compare the experimental results with the theoretical model and make prediction of the real system from modelling.

The reason of the unavailability of this information might be that the system is not so simple. For a confined plasma system, several types of instabilities (sands) coexist. Perhaps there's no easy way to simplify the real system, but a systematic scan on the operational parameters, such as field strength, ion species, distribution of heat source, etc., might be beneficial to addressing this issue.

3. Ambiguity between avalanches and other fluctuations

The reason that existing core-plasma experiments were carried in low-performance modes is that large fluctuations such as MHD instabilities won't be excited. If they are excited, it would be unclear if the observed feature is due to avalanches or them. The experiment on LAPD is also a good example, where the existence of periodicity of the fluctuations make us doubt if it's a large wave packet or avalanches. However, in a real system for MFE purpose, often such large fluctuations do coexist with our target phenomena. Therefore, how to characterize avalanches in those regimes would eventually become an important issue.

Perhaps we can extrapolate the characteristic parameters from the quiet regime to these regimes. This, however, relies on charactering the fundamental SOC model. Another method is to separate avalanches with those large waves by their different behavior like self-similarity and non-periodicity.

4. No solid experimental results in linear devices

While the low L/Δ ratio in linear devices is temporarily difficult to resolve, the simple geometry of the device still make it appealing to search for avalanches in linear devices. One possible way is to analyze the statistical features, such as Hurst parameter, the PDF of fluctuations and the autocorrelation function in the quiet regime (no large waves).

5. Little investigation on shear effect

In the sandpile models, suppression of large avalanche events by a shear layer is an important result. However, few experiments are carried on this topic. The discrepancy between existing experimental and the modelling results have not been fully understood yet.

More interestingly, besides the externally applied shear flow through plasma biasing, the zonal flows in confined plasmas also provide a natural shear environment. There are already some theoretical work on this issue (reviewed in [1]). Studying the influence of zonal flows on avalanches is also an important issue.

D. Beyond the scope of current researches

While the current experimental researches are more about identifying SOC features in the MFE plasmas, we should ask what we might be able to do beyond that.

1. Determine the SOC regime

If the parameters of the underlying mechanism of SOC is available, we may be able to determine the SOC regime for a certain system and try to find if there's universal rule for similar devices. In particular, important questions include:

(1) How do we estimate the avalanche contribution to the total transport?
(2) By increasing inflow, when does a system enter SOC regime?
(3) Similarly, when does a system enter the "strong drive" regime?

2. Avalanche control

If the SOC regime is clearly characterized, we might be able to control the avalanches. For example, shear layer is an existing concept of controlling the avalanche transport. Moreover, we may try to reduce avalanches by relaxing the gradient profile in other channels such as collisions or enhance avalanches by applying heat or particle sources. With these we might be able to search for direct evidence that avalanche transport leads to the important phenomena like formation of pedestal, profile stiffness and Bohm diffusivity scaling. Being able to control avalanches would also benefit us on controlling the total transport, and thus confinement, of the MFE reactors.

E. Summary

Due to the insufficiency of existing diagnostics, current experimental researches on avalanches are still mostly on identifying SOC features in MFE devices. While technological breakthrough is not easy, I believe a parameter scan can benefit us on understanding the underlying mechanism (model) of SOC. Once understanding the mechanism, we can try to determine the SOC regime for the MFE plasma system and control avalanche transport in the MFE plasma system.

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