# Enhanced Confinement Phenomenology in Magnetic Fusion Plasmas: is it Unique in Physics?

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**Abstract** The sandpile paradigm, coupled to some of the key concepts and techniques of modern statistical physics, can be used to construct models that generate many of the distinctive observed elements of tokamak confinement phenomenology, as well as non-Gaussian transport and fluctuations. The similarities are substantial, and can be quantified. An essential feature of these models is that they rely on avalanching transport or statistical clustering. Current observations of avalanching transport and non-Gaussian fluctuations in tokamaks may thus be deeply linked to fundamental features of tokamak plasma enhanced confinement, such as edge pedestals and ELMs. The fact that such features can be generated by few-parameter models is also significant.

## 1. Introduction

The search for simple physical systems whose confinement phenomenology resembles that of tokamaks is important for at least two reasons. First, it enables the identification of a minimal set of physical principles that underlie different aspects of tokamak behaviour. This is otherwise difficult, given the wide range of interacting plasma physics mechanisms, operating on diverse lengthscales and timescales and in nonlinear regimes, that combine together to produce the effects observed. Second, it assists the identification of a small set of key control parameters - perhaps representing the combined effects of many experimental variables - whose values determine system behaviour.

There is now substantial experimental evidence that simple diffusive and Gaussian paradigms for the transport arising from turbulence in tokamak plasmas are insufficient to describe all the confinement phenomenology observed. Examples include avalanching transport[1,2], which is also seen in some numerical simulations[3-5]; while measurement and analysis of edge plasma turbulence, see for example Refs.[6-10], provides evidence for non-Gaussian probability distribution functions that are often long-tailed, and may be inverse power law. In parallel to these developments, there remains the outstanding physics question arising from observations of tokamak confinement: namely, why the distinctive characteristics - enhanced confinement regimes, edge pedestals, ELMs, and so on - arise at all. For example, are these phenomena sufficiently generic that their existence could in principle have been predicted by analogy with other physical systems? Current developments in statistical physics are now being used successfully to address such questions, and furthermore suggest that avalanching transport and the physical principles underlying enhanced confinement in tokamaks may be deeply linked[11]. These developments also provide pointers to the underlying control parameters. Here we report recent work[11,12] on two key aspects.

## 2. Avalanching and enhanced confinement in tokamaks

Linkage is emerging between rapid, nonlocal, nondiffusive transport seen in tokamaks, and the overall confinement phenomenology including edge pedestals, enhanced confinement, ELMs, and internal transport barriers[11]. It appears that the latter set of phenomena should no longer be considered unique to magnetically confined fusion plasmas. For example, Fig.1 shows the time averaged profiles yielded[11] by a simple sandpile algorithm[13] when its sole control parameter *L* (a lengthscale for rapid redistribution, which may be considered as a proxy for turbulent vortex size, for example) is varied.

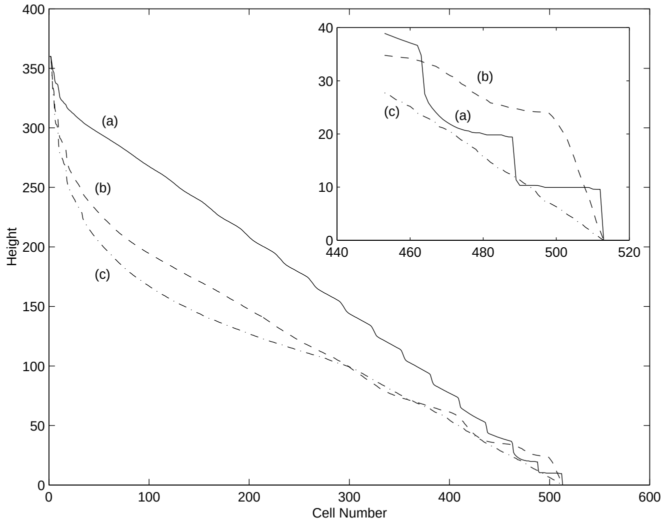

*FIG.1. Time averaged height profiles of the 512 cell sandpile[11] for L = (a) 50, (b)150, (c)250. Inset: edge structure.*

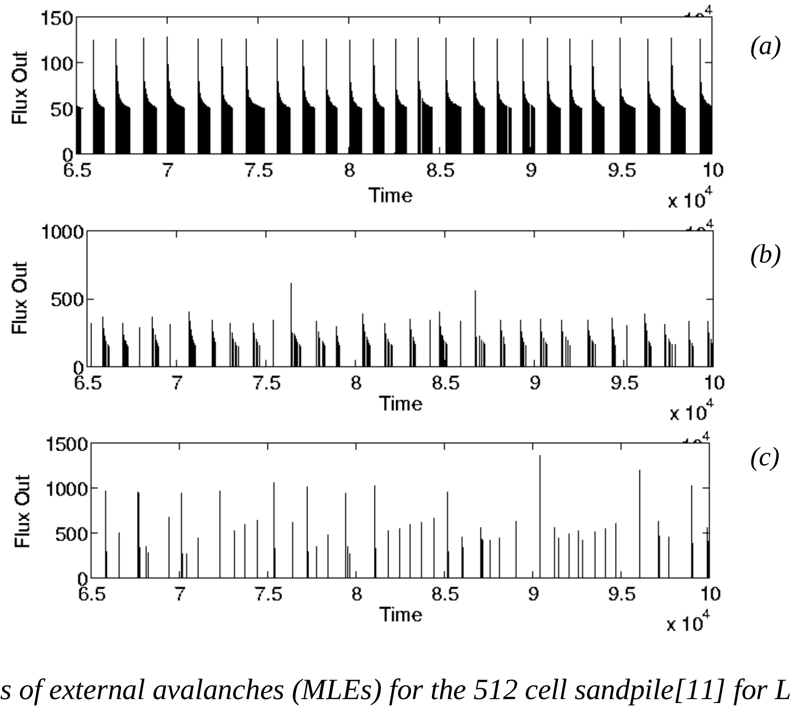

*FIG.2. Time series of external avalanches (MLEs) for the 512 cell sandpile[11] for L = (a) 50, (b) 150, (c) 250. Plots show magnitude of flux leaving the sandpile, versus time.*

The existence of enhanced confinement and edge pedestals for this sandpile is complemented by the time series for its external avalanches ("mass loss events", MLEs - Fig.2), whose appearance and role mimics that of ELMs. Not only does the character of the MLEs correlate with the confinement properties of the sandpile; there are also quantitative correlations. For example, frequency can be calculated for MLEs using the method employed to calculate ELM frequencies on JET[14], and Fig.3 shows the scaling of the frequency of the MLEs with stored energy in the sandpile. This resembles that obtained for the scaling of ELM frequency with stored energy in JET for certain discharges[15].

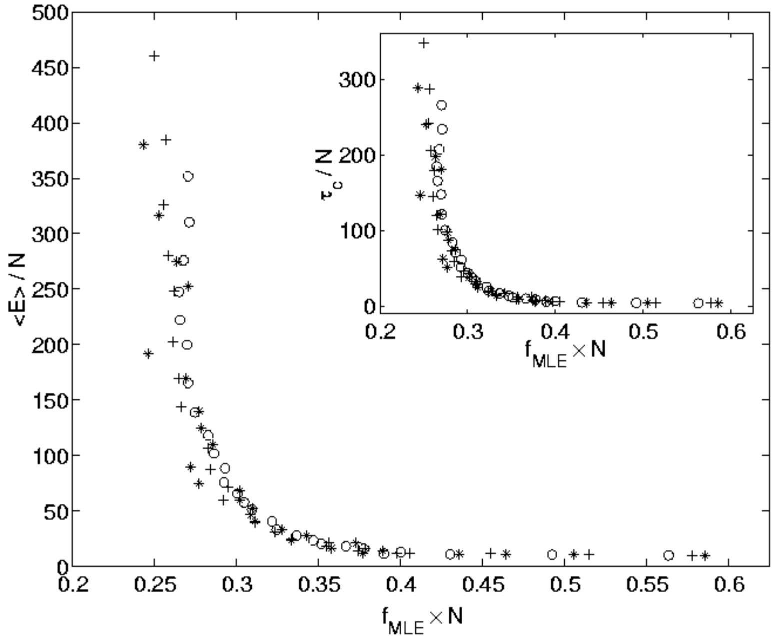

*FIG 3. Averaged stored energy versus frequency of mass loss events (MLEs) for the sandpile[11] with number of cells N = 512, 4096, and 8192. Normalisation with respect to N demonstrates robust scale invariance of this phenomenology. Inset: confinement time versus MLE frequency.*

The existence of such extensive tokamak-like phenomenology[11], emergent from a very simple system[13], is interesting. Insofar as the phenomenological resemblance is close, there is more to be learnt. A minimalist interpretation starts from the premise that this sandpile algorithm provides a simple one-parameter model for studying generic nonlocal transport, conditioned by a critical gradient, in a macroscopic confinement system. Changing the value of the single control parameter *L* then corresponds to altering the spatial range over which the transport process operates. It then follows from the above results that this may be the minimum requirement to generate the aspects of tokamak-like confinement phenomenology described. This is significant, but one can also consider a more far-reaching interpretation. This maximalist interpretation attaches greater weight to recent observations [1,2,7] of avalanching transport in tokamaks and in largescale numerical simulations[3-5] thereof, and therefore regards the avalanching transport that is built into sandpile algorithms as an additional point of contact with magnetically confined plasmas. One would then infer from the present results[11] that tokamak observations of avalanching transport are deeply linked to the existence of enhanced confinement and ELMs. Furthermore the existence of the single control parameter *L*, governing the confinement phenomenology and arising from the rapid transport, would then hold out the prospect that a synthesis of the many experimental parameters into one underlying parameter may be possible.

## 3. Avalanching and fluctuation measurements in tokamaks

A second line of research aims to identify the minimal requirements for statistical processes that can generate nondiffusive avalanching transport and can reproduce, for example, the non-Gaussian features of density fluctuation and flux fluctuation measurements in tokamaks. It has recently been shown[12] that statistical clustering of transport events, described for example in terms of contemporary models for population dynamics, is sufficient to generate some of the observed phenomenology. For example, Fig.4 shows the time series of time integrated local height fluctuations from a simple sandpile model that can be characterised in these terms. The mathematical derivation of this trace from the local sandpile height is equivalent to that of the random walk constructed from local edge density measurements in the DIII-D tokamak in Ref.[10]. There is qualitative similarity between the output Fig.4 of the sandpile model and the tokamak measurements of Fig.2(a) of Ref.[10]. Calculation of the Hurst exponent of the density fluctuations in the sandpile[12] and the tokamak[10] indicates the presence of correlations that have non-Gaussian fractal behaviour. This implies that processes distinct from Brownian motion affect the transport in both systems.

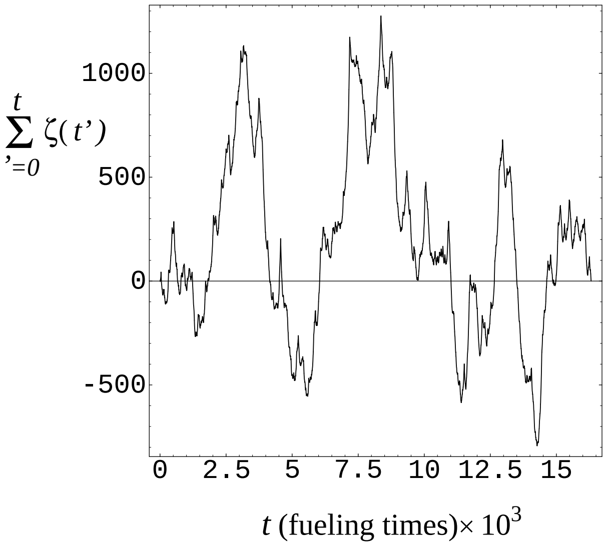

*FIG. 4. Time integrated local height fluctuations in the model of Ref.[12].*

The sandpile model of Ref.[12] resolves behaviour on distinct timescales, so that statistical analyses equivalent to fast particle transport studies can be carried out. Multichannel measurements indicate the presence of self organising long-lived density fluctuations that are spatially extended, and whose propagation across the sandpile is frozen-in.

## 4. Conclusions

The sandpile paradigm, coupled to some of the key concepts and techniques of modern statistical physics, can be used to construct models that generate many of the distinctive observed elements of tokamak confinement phenomenology, as well as non-Gaussian transport and fluctuations[11,12]. The similarities are substantial, and can be quantified. An essential feature of these simple models is that they rely on avalanching transport or statistical clustering. One may infer that current observations[1,2,6-10] of avalanching transport and non-Gaussian fluctuations in tokamaks, far from being curiosities, may be deeply linked to fundamental features of tokamak plasma enhanced confinement, such as edge pedestals and ELMs. The fact that such features can be generated by few-parameter models is also significant.

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