Observation of Avalanchelike Phenomena in a Magnetically Confined Plasma

P. A. Politzer
General Atomics, P.O. Box 85608, San Diego, California 92186-5608
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Electron temperature fluctuations seen in a magnetically confined tokamak plasma have some of the characteristics of the avalanchelike events sometimes associated with self-organized criticality, including intermittency, large space and time scales, "$1/f$" spectra, large tails in the autocorrelation function, and clear evidence of radial propagation.

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Several distinct paradigms are available for transport of mass, momentum, energy, or other quantities across a plasma confined by a magnetic field [1]. Among these are diffusion (driven by Coulomb collisions or by microturbulence), convection (magnetic stochasticity, convective cells), relaxation oscillations [sawteeth, edge localized modes (ELMs)], and the phenomena identified as "avalanches." This is shorthand for intermittent transport events which occur on a range of spatial scales up to the system size. Avalanches are a key ingredient in the theory of self-organized criticality (SOC), but their occurrence is not limited to SOC systems.

The intuitive picture of avalanches is based on modeling of sandpiles [2] or on observation (preferably remote) of actual avalanche events. In this picture, the principal qualitative characteristic of avalanches is that transport occurs through discrete, intermittent events. These events occur on all space and time scales, up to spatial scales corresponding to the system size. The expectation is that the frequency spectrum should show scaling behavior, $f^{-\alpha}$, most characteristically with $\alpha \sim 1$. The autocorrelation function at any particular location should show an extended tail at large delay times. Finally, avalanche events should be seen to propagate with finite velocity in the direction opposite to the gradient (i.e., downhill).

There have been several reports of simulations of plasma instability which show these characteristic behaviors in magnetically confined plasmas [3,4]. Consistent with experimental procedures, these simulations constrain the sources rather than the resulting profiles, and so allow for intermittent behavior. There have also been experimental measurements of noise in plasma density and potential measurements with some of the expected characteristics—particularly the spectral behavior [5,6]. Most of these measurements were made in the edge region of tokamaks and stellarators, which is accessible to material probes. Thus far, these observations have been restricted to single-point measurements and so could not show evidence of radial propagation.

This Letter reports the initial observations of the radial propagation of avalanchelike events through most of the cross section of a magnetically confined plasma in the DIII-D tokamak. These events have all of the qualitative characteristics expected for avalanches: intermittency, large spatial scale, characteristic spectra, enhanced autocorrelation, and radial propagation.

Calculations and models for avalanches as applied to tokamak plasmas provide a qualitative picture of what to look for, but are not yet sufficiently detailed to give quantitative predictions. Thus a search was undertaken to find evidence of avalanches under the most likely conditions in the DIII-D tokamak plasma. Although there are several instruments on DIII-D which look at fluctuations, the electron cyclotron emission (ECE) diagnostic, which provides a direct measure of the local T_e, was used because of two favorable circumstances [7]. First, this is a multichannel instrument, covering essentially the entire plasma profile from center to edge; the spatial resolution of each channel is roughly $\delta r/a \sim 0.03$, where a is the plasma minor radius. Second, long signal records (several seconds) with a high sampling rate (50 kHz or better) are possible. To perform the required analyses, an extended quiet period is required with no MHD activity, no sawteeth, no ELMs, no changes in plasma position or heating power.

Among the few suitable discharges are the ones used for current drive and transport experiments using the DIII-D electron cyclotron heating (ECH) system, in the preliminary phase before the ECH is turned on. Generally, there is an extended period of 0.5 to 1.5 s, during which the plasma is weakly heated by a single neutral beam and is maintained under steady external conditions. A slow internal evolution of temperature, density, and current profiles is observed. Characteristic profiles for such a discharge are shown in Fig. 1. During the period 1.0 to 2.0 s, the plasma is heated by a single 2.65 MW neutral deuterium beam source. Also, there is a slow evolution of the equilibrium profiles. The safety factor at the magnetic axis decreases from $\sim$2.0 to $\sim$1.0, and the central T_e rises from $\sim$3 to $\sim$4 keV. The plasma has no localized steep gradients in density or temperature. The energy confinement time is $\sim$75 to 85 ms.

The observable events which fit the characterization of avalanchelike phenomena have durations in the approximate range of 2 to 50 ms. If they exist, events of shorter duration are obscured by instrumental noise. Longer-lasting events are difficult to distinguish from the

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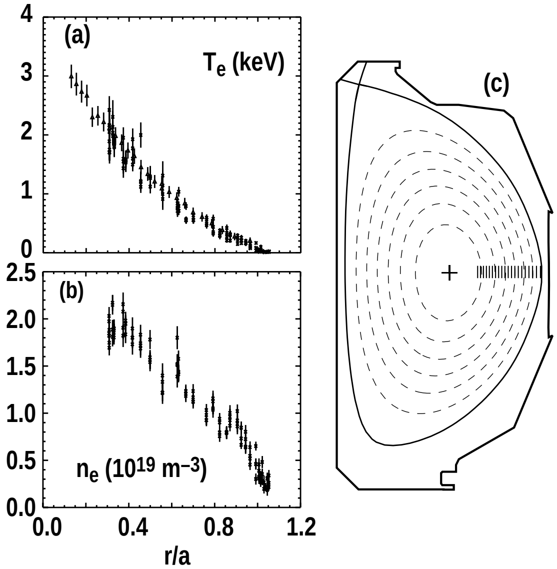

FIG. 1. Characterization of a slowly evolving, extremely quiet phase of DIII-D discharge 96146 at 1.15 s. Profiles of (a) T_e (keV), and (b) electron density (10^{19} m^{-3}); the data window is ± 15 ms, so several measurements are shown for each location. (c) The plasma shape at 1.15 s, in the DIII-D vacuum vessel. The approximate measurement locations of the ECE channels used in this analysis are indicated by short vertical bars.

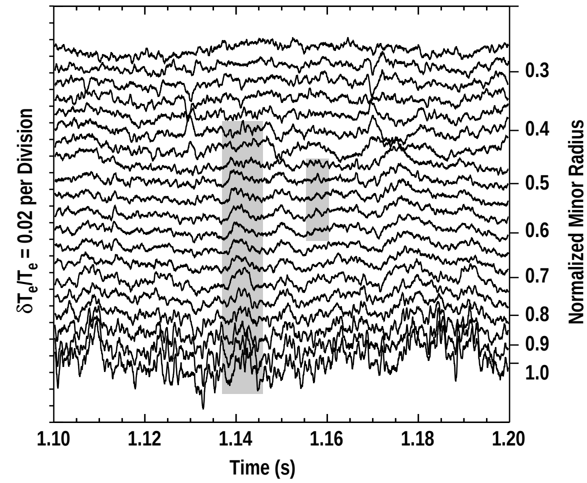

FIG. 2. T_e fluctuations for ECE channels between $r/a \approx 0.25$ and the plasma edge, for a 100 ms interval. The left scale indicates the amplitude for each channel (2% per division). The radial locations of the channels are indicated by the scale on the right. The dc level and secular time variation are removed, and the data are normalized to the mean for each channel. A 0.5 ms centered rectangular smooth is applied to the plotted data.

secular evolution of the discharge. The following paragraphs discuss some characterizations of these data in the context of anticipated avalanche properties.

Intermittency and spatial scale.—One of the predicted properties of avalanches is the intermittent appearance of coherent structures, propagating radially, with scale lengths up to the size of the plasma. Figure 2 displays the T_e fluctuations for a 100 ms interval, normalized to the time-averaged signal for each channel [$\delta T/T \equiv (T_e - \langle T_e \rangle_{100})/\langle T_e \rangle_{100}$, where $\langle T_e \rangle_{100}$ is the 100 ms centered moving average]. The rms fluctuation level is 1.0% over most of the plasma radius ($r/a = 0.25$–0.7), rising to 2.5% at the plasma edge. Although this is a very quiet plasma, some larger fluctuations are seen to be correlated across several channels or over a significant portion of the plasma (for example, the highlighted small event at ~ 1.158 s or the large one at ~ 1.141 s). Figure 3 provides a qualitative comparison between a model calculation and these observations. Figure 3(a) shows the results of a computation of the dynamics of resistive pressure gradient driven turbulence [3]. The presence of disturbances with large spatial and temporal scales that propagate radially outward is clearly seen. Figure 3(b) shows the same data as plotted in Fig. 2. In both cases, the radial span covers most of the plasma minor radius and the time span is a fraction of the resistive time. The data in Figs. 2 and 3(b) indicate that the events cover the radial range from the resolution of the instrument to the full plasma radius. Measured in terms of the resistive time, these observations and the calculations of Ref. [3] disagree. The characteristic time for crossing most of the plasma is $1/40\ \tau_R$ in the modeling, and $1/4000\ \tau_R$ in the experiment. A possible conclusion is that τ_R is not the relevant characteristic time.

Spectrum.—Another expected property is the scaling character of the Fourier spectrum of the turbulence. Scaling or self-similar behavior is associated with a power-law spectrum: If $F = Cf^{-\alpha}$, then the transformations $C = cC'$ and $f = c^{1/\alpha} f'$ give a result indistinguishable from the original, $F = C' f'^{-\alpha}$. Figure 4 displays the Fourier transform of the T_e for a 1.0 s record at $r/a \approx 0.48$. Two distinct spectral ranges are apparent. In the range of ~ 10 to 200 Hz, the spectrum shows a f^{-1} dependence. At

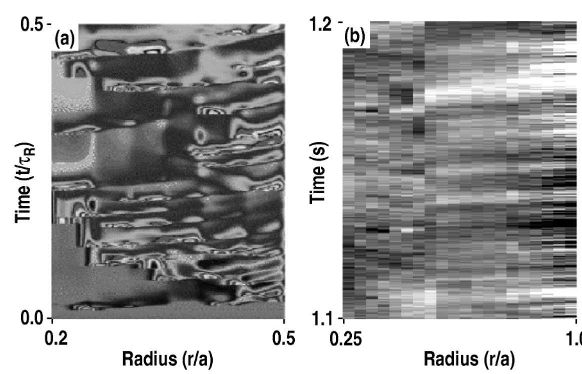

FIG. 3. Contour plots of (a) density variation versus radius and time for computed model of resistive pressure gradient driven turbulence (from Ref. [3]) and (b) relative T_e variation versus radius and time from ECE diagnostic (the same data as in Fig. 2). The data in (b) have been clipped at ± 0.02; white is ≥ 0.02, black is ≤ -0.02. In (a), time is in units of the resistive time, $\tau_R = a^2 \mu_0/\eta$; in (b), $\tau_R \approx 20$ s.

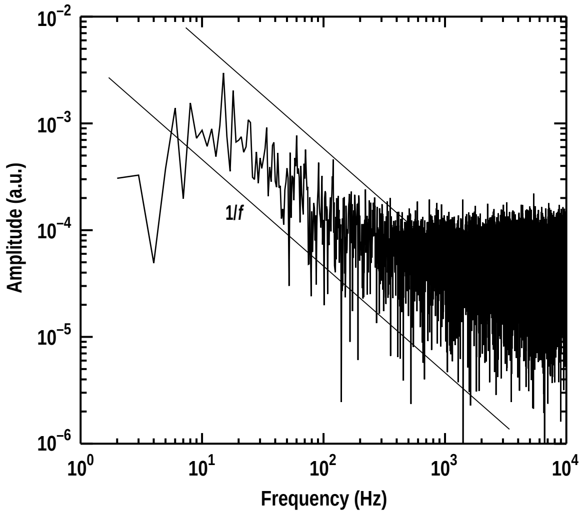

FIG. 4. Fourier spectrum of the fluctuating ECE signal for the 1.0 to 2.0 s record of a channel at $r/a \approx 0.48$.

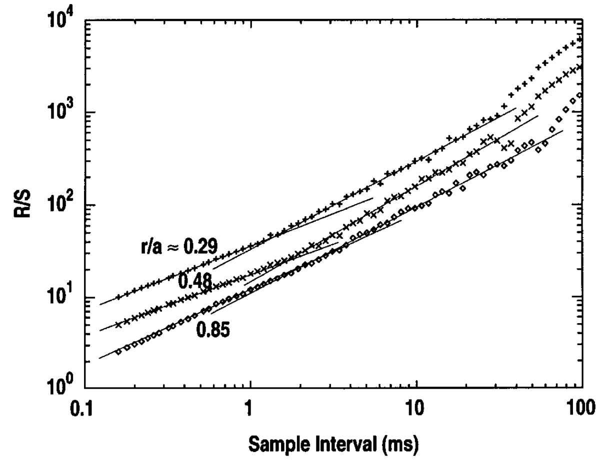

FIG. 5. Mean reduced range versus sample size at $r/a \approx 0.29$, 0.48, and 0.85 for the 1.1–1.2 s interval. The signal is digitized at a 50 kHz sampling rate, so a 1 ms interval contains 50 samples. No averaging is done. The slopes of the fitted straight lines give the values of H referred to in the text.

higher frequencies, above ~400 Hz, the spectrum is flat, corresponding to instrumental noise.

Long-time autocorrelation.—The statistical behavior of avalanches is characterized by the condition that large-scale events occur more often than might be expected, for example, for a Gaussian-Markov probability distribution. This can be characterized by the appearance of a power-law tail in the long-time limit of the autocorrelation function, $\rho(\tau) \propto \tau^{-\beta}$, where τ is the lag. This power-law dependence is also an indicator of scaling or self-similar behavior. A robust technique for quantifying this behavior is the rescaled range (R/S) analysis which yields the Hurst parameter, H [8]. H is related to the exponent of the tail of the autocorrelation function by $H = 1 - \beta/2$. Noise with a Gaussian-Markov distribution should give $H = 1/2$. $H < 1/2$ indicates the possibility of long-time anticorrelation. The results of this analysis for three different radial locations are shown in Fig. 5, where H is the slope of the curve. The appearance of regions of constant slope in this plot indicate self-similar behavior. On all three curves, there are discontinuities in slope at about a 2-ms sample interval and at about 40 ms. The region between 2 and 40 ms samples corresponds to $1/f$ region in Fig. 4. In this range, the distribution of transient events is strongly weighted to larger excursions. The Hurst parameters for this range of sample sizes are $H = 0.95$, 1.03, and 0.93. The behavior for samples larger than about 40 ms is not meaningful because of the limited number of such samples in the total record used. The behavior of short samples corresponds to the white noise region in Fig. 4. However, the R/S analysis indicates that this is not normally distributed. The Hurst parameters are $H = 0.70$, 0.66, and 0.82 for the channels at $r/a = 0.29$, 0.48, and 0.85, respectively. To test the algorithm used in the R/S analysis, the $r/a = 0.48$ data record was shuffled in time and reanalyzed. The resulting value of H is 0.53, close to the expected value of 0.5.

Radial propagation.—The fundamental characteristic of a single avalanche event is that it moves in the radial direction. In order to verify this motion and to determine quantitatively, but in an average sense, the radial speed of the avalanches, the cross correlation between ECE channels at different radial locations is calculated. Figure 6 shows the pairwise cross correlation of each ECE channel with a channel at $r/a = 0.45$, over a range of lag times -5 to $+5$ ms. The motion of the position of maximum cross correlation to larger lag as one moves outward on the profile indicates an outward propagation. Note that for

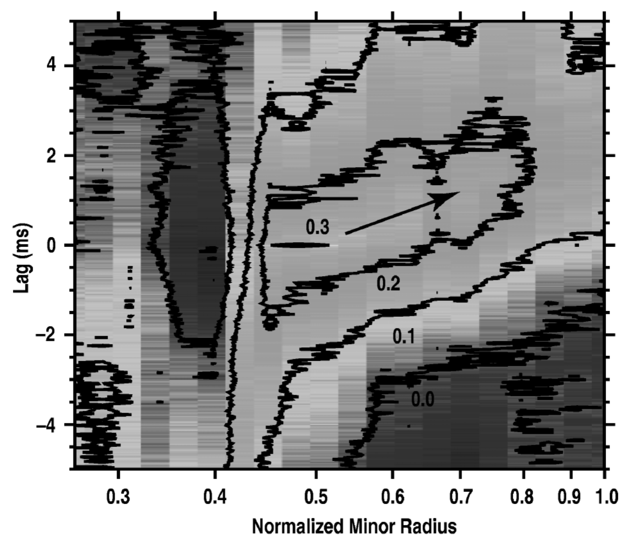

FIG. 6. Contours of the cross correlation function between T_e for each ECE channel and the reference channel at $r/a = 0.48$. The arrow indicates the propagation of the maximum cross correlation.

the region of large cross correlation shown here (roughly $1/3 \leq r/a \leq 2/3$) the effective velocity (the velocity of the peak of the cross correlation) is approximately constant at $\sim$100 m/s. A similar analysis using a reference channel near the plasma edge indicates that the effective velocity in that region ($0.75 \leq r/a \leq 1$) increases to $\sim$1000 m/s.

The observations summarized here present strong evidence for the presence of avalanchelike events in the magnetically confined DIII-D tokamak plasma. Measurements of low frequency T_e fluctuations show intermittent, large radial-scale events, with a $1/f$ spectrum, with strong evidence from the R/S analysis of a high recurrence rate for large events, and with clear demonstration of radial propagation from the cross-correlation analysis.

Some other characteristics of these observations should be noted. The apparent effective radial velocity is slow, 2 orders of magnitude below the sound speed. The velocity varies from 0.1 to 1 times the diamagnetic velocity as the observation point moves from the plasma core to the edge. The toroidal and poloidal structure of these disturbances is unknown. Electron heat transport along magnetic field lines is fast enough in comparison with the duration of the events seen here that there should be little variation within a magnetic surface, but a direct comparison between different fluctuation diagnostics is needed to confirm this. The absence of variation within a flux surface means that the plasma rotation, which is important in analysis of brief events [6], is not a consideration here except, perhaps, close to the plasma axis.

It should be noted that the behavior exemplified by Fig. 2 is commonly seen in DIII-D discharges, but in most cases the added presence of much larger phenomena such as Mirnov oscillations, sawteeth, or ELMs precludes further analysis of the low-level fluctuation characteristics.

An important question yet to be resolved is the importance of these avalanche events in energy transport and the overall power balance of the plasma. Even though the rms T_e fluctuation is small, the large Hurst parameter suggests that a significant amount of energy is carried by the largest events. To determine the average power carried in these events, simultaneous and colocated measurements of density and temperature fluctuations are needed. Finally, better analysis techniques are needed in order to study these phenomena in the presence of larger, but more coherent MHD fluctuations.

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[1] John Wesson, *Tokamaks* (Clarendon Press, Oxford, 1987).

[2] P. Bak, C. Tang, and K. Wiesenfeld, Phys. Rev. Lett. **59**, 381 (1987); Phys. Rev. A **38**, 364 (1988); L. P. Kadanoff, S. R. Nagel, L. Wu, and S-M. Zhou, Phys. Rev. A **39**, 6524 (1989); H. M. Jaeger, C-H. Liu, and S. R. Nagel, Phys. Rev. Lett. **62**, 40 (1989); T. Hwa and M. Kadar, Phys. Rev. A **45**, 7002 (1992); M. V. Medvedev, P. H. Diamond, and B. A. Carreras, Phys. Plasmas **3**, 3745 (1996); B. A. Carreras, V. E. Lynch, P. H. Diamond, and M. Medvedev, Plasmas **5**, 1206 (1998).

[3] B. A. Carreras, D. Newman, V. E. Lynch, and P. H. Diamond, Phys. Plasmas **3**, 2903 (1996).

[4] X. Garbet and R. E. Waltz, Phys. Plasmas **5**, 2836 (1998).

[5] B. A. Carreras, B. van Milligen, M. A. Pedrosa, R. Balbin, C. Hidalgo, D. E. Newman, E. Sanchez, M. Frances, I. Garcia-Cortes, J. Bleuel, M. Endler, S. Davies, and G. F. Matthews, Phys. Rev. Lett. **80**, 4438 (1998); B. A. Carreras, B. Ph. Van Milligen, M. A. Pedrosa, R. Balbin, C. Hidalgo, D. E. Newman, E. Sanchez, M. Frances, I. Garcia-Cortes, J. Bleuel, M. Endler, C. Ricardi, S. Davies, G. F. Matthews, E. Martines, V. Antoni, A. Latten, and T. Klinger, Phys. Plasmas **5**, 3632 (1998).

[6] T. L. Rhodes, R. A. Moyer, R. Groebner, E. J. Doyle, R. Lehmer, W. A. Peebles, and C. L. Rettig, Phys. Lett. A **253**, 181 (1999).

[7] Z. Wang, J. Lohr, G. L. Bell, C. Hsieh, J. Luo, R. E. Stockdale, J. B. Wilgen, and J. Zhang, in *Proceedings of the 9th Workshop on Electron Cyclotron Emission and Electron Cyclotron Heating, Borrego Springs, 1995* (World Scientific, Singapore, 1995), p. 427.

[8] H. E. Hurst, Trans. Am. Soc. Civ. Eng. **116**, 770 (1951); B. B. Mandelbrot and J. R. Wallis, Water Resour. Res. **4**, 909 (1969); **5**, 422 (1969); **5**, 967 (1969).