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Reduced intermittency in the magnetic turbulence of reversed field pinch plasmas

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The statistical temporal properties of broadband magnetic turbulence in the edge of reversed field pinch (RFP) plasmas are significantly altered when global magnetohydrodynamic tearing modes and magnetic relaxation are reduced. Standard RFP plasmas, having relatively large tearing fluctuations, exhibit broadband intermittent bursts of magnetic fluctuations in the bandwidth $f < 1.5$ MHz. When the global tearing is reduced via parallel current drive in the edge region, the magnetic turbulence is much less intermittent and has statistical behavior typical of self-similar turbulence (like that expected in self-organized criticality systems). A connection between intermittency and long wavelength plasma instabilities is therefore implied. © *2005 American Institute of Physics*.

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Magnetically confined plasmas are well known to exhibit turbulent fluctuations and transport of energy and particles with a bursty nature: i.e., transport occurs in irregularly distributed short-lived random events. The properties of the turbulence reflect its underlying origin, which generally remains not well understood. An important, potentially discriminating property is the appearance of self-similarity in the fluctuations and transport at different temporal and spatial scales. A quantity b is self-similar in time if the distribution of its increments, $\delta_\tau b = b(t+\tau) - b(t)$, collapses to one statistical distribution for each time scale τ. For example, in the phenomenological Kolmogorov theory,[1] this distribution is Gaussian, reflecting the random nature of the turbulence interaction. Experimental evidence from several laboratory toroidal magnetic configurations (primarily tokamak and stellarator plasmas) supports a characterization of edge plasma turbulence as having a self-similar nature,[2] while other evidence from reversed field pinch (RFP) plasmas[3] indicates self-similarity is not a general feature of toroidal plasmas due to the presence of intermittency in turbulence time series.[4,5] One implication for a lack of self-similarity is that the turbulence driven transport cannot be described within a self-organized critically (SOC) paradigm,[6,7] which models avalanche-like transport in marginal-stability systems. An SOC-like process has also recently been proposed for magnetic helicity (or parallel current) transport in a description of the Taylor relaxation of RFP plasmas.[8]

This paper reports on the statistical properties of broadband magnetic turbulence measured in the edge of two types of RFP plasmas: standard ones exhibiting a relaxation behavior and reduced-tearing plasmas in which relaxation is suppressed. Standard RFP plasmas exhibit magnetic relaxation through a nonlinear process involving resistive magnetohydrodynamic (MHD) tearing instabilities, which generate $\sim 1\%$ fluctuations in the magnetic field.[3] The broadband magnetic turbulence exhibits a non-self-similar character, much like that previously reported for electrostatic turbulence and particle transport in the edge plasma.[4,5,9] In contrast, the magnetic turbulence is less intermittent and nearly self-similar at different scales when the MHD tearing is reduced by roughly a factor of three (through adjustment of the plasma current drive). The high frequency fluctuation amplitude and coherence length are also decreased, and the spectral power density decays with frequency more rapidly. These observations suggest a connection between the global tearing and the broadband, smaller amplitude magnetic turbulence. Previous work showed that the intermittency in electrostatic turbulence correlates in time with distinct magnetic relaxation events.[5] This paper also reports that standard RFP data selected to avoid the largest relaxation events have the same non-self-similar character. The changes observed in reduced-tearing plasmas are therefore not merely the result of large-event suppression.

The plasmas for this work were formed in the Madison symmetric torus (MST), a circular cross-section torus with minor and major radii $a = 0.5$ m and $R = 1.5$ m and plasma current capability ≤ 0.5 MA.[10] Two types of plasma are compared. The first is the standard RFP formed by steady toroidal induction. Standard plasmas are self-organized via a dynamo process involving MHD tearing.[3] The resulting magnetic turbulence is also the main cause for energy and particle transport in most of the plasma volume.[11] The second type of plasma is formed by modifying the inductive current drive to reduce the tearing instability, a technique

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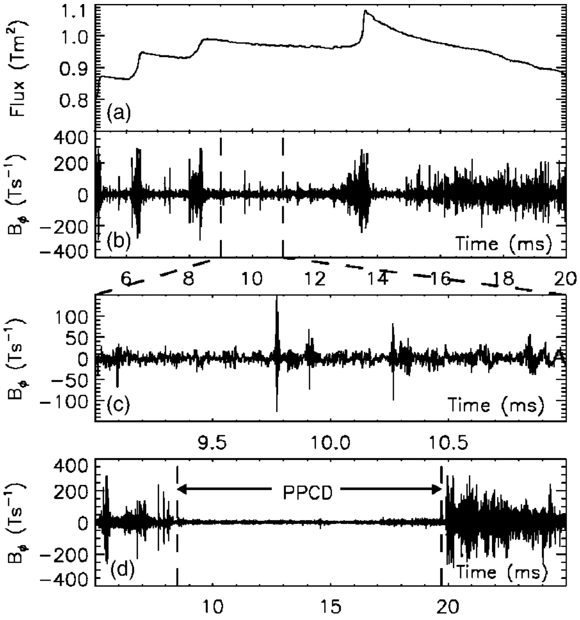

FIG. 1. (a) Typical evolution of Φ for a standard plasma. (b) $\dot{B}_\phi$ signal for the same plasma. (c) Magnified view of $\dot{B}_\phi$ in (b). (d) $\dot{B}_\phi$ for a PPCD plasma.

called pulsed poloidal current drive (PPCD).[12,13] The magnetic turbulence is decreased, which reduces the fluctuation-induced heat and particle transport.[14]

This paper focuses on the change in the statistical properties of broadband magnetic fluctuations when PPCD is applied. The magnetic fluctuations B_ϕ are measured by an array of four pickup coils which sense the toroidal component B_ϕ of the magnetic field at the plasma boundary. The frequency bandwidth is 1.5 MHz. The data are from plasmas with current ≈ 0.5 MA and density $n_e \approx 1 \times 10^{19}$ m^{-3}. The core electron temperature is ≈ 0.4 keV in standard plasmas and ≈ 1 keV in PPCD plasmas. Reduced intermittency is also observed in 0.4 MA PPCD plasmas. Although the pickup coils are located at the plasma surface, the power spectra measured by probes inserted in the outer region of low current 0.2 MA plasmas are essentially identical to those measured by surface coils. This is likely to be the case at higher current as well.

Standard MST plasmas exhibit large, distinct relaxation dynamo events, called sawteeth,[15] during which substantial toroidal magnetic flux, $\Phi = \int_0^a 2\pi r B_\phi(r) dr$, is generated, as shown in Fig. 1(a). The magnetic fluctuation amplitude increases in time leading up to and especially during the sawtooth crash [Fig. 1(b) shows $\dot{B}_\phi$]. Smaller, less distinct bursts also appear between sawteeth, as shown in the expanded time trace of Fig. 1(c).

The situation in PPCD plasmas is completely different. PPCD is applied through a programmed ramp of the toroidal field to create poloidal induction in the outer region of the plasma.[12,13] The added induction replaces dynamo current generation in the standard reversed field pinch (RFP), and the tearing fluctuations are reduced. The $\tilde{B}_\phi$ fluctuation is less bursty and reduced in amplitude during PPCD, as shown in Fig. 1(d). PPCD is inherently transient, so the reduced fluctuation period only lasts ~10 ms (9–19 ms in Fig. 1). Note that this is longer than the typical sawtooth period in standard plasmas.

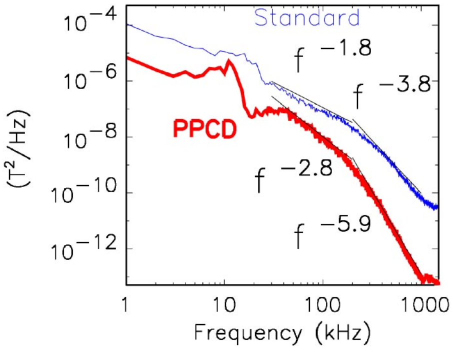

FIG. 2. (Color online). Power spectra of $\tilde{B}_\phi$ in standard (thin line) and PPCD (thick line) plasmas.

The reduction in magnetic fluctuation during PPCD is broadband, with high frequency components more strongly suppressed. The shape of the magnetic fluctuation frequency power spectrum therefore changes substantially, as shown in Fig. 2. These ensemble-averaged Fourier power spectra are formed by averaging 1 ms intervals between $t = 9$–18 ms, i.e., during the current flattop for standard plasmas and the quiescent periods for PPCD plasmas. The ensembles include multiple intervals from ~10 plasmas of each type.

Three distinct regions in the $\tilde{B}_\phi$ power spectra are identified. The first is a peak in the 10–30 kHz range, corresponding to the toroidal rotation of the dominant poloidal mode number $m=1$ tearing modes (only rotating plasmas are analyzed here). This peak is broad since there are several comparably sized dominant modes of similar wavelength, and because the mode rotation speed varies during the sawtooth cycle. From 30 kHz to ~200 kHz, the standard plasma spectrum shows a power law decay $\propto f^{-\alpha_1}$ with $\alpha_1 \approx 1.8$. A transition to a steeper power law, with larger $\alpha_2 \approx 3.8$, occurs for $f \gtrsim 300$ kHz, perhaps indicating dissipation plays an important role at highest frequencies. These characteristic exponents, as well as the normalized fluctuation amplitude $\tilde{B}/B$, vary somewhat with plasma current and possibly other parameters. A systematic study has not yet been performed to clarify these dependencies. In particular, $\tilde{B}/B$ is predicted to depend on the mean-field B for homogeneous MHD turbulence.[16]

The fluctuation power in PPCD plasmas, at the same plasma current, is reduced in all three spectral regions, still remaining above the noise threshold. The dominant tearing modes are reduced ~threefold but have roughly the same frequency since the plasma rotation does not change much. However, the exponents of the power law decay at higher frequencies are quite different, with $\alpha_1 \approx 2.8$ and $\alpha_2 \approx 5.9$. Two statistical analysis techniques are used to reveal possible intermittent behavior in the magnetic field: analysis of the statistical distribution of the laminar times (defined as those times elapsed between two bursts in the fluctuating signal) and of the probability distribution function (PDF) of the signal differences. These techniques are often applied to fluctu-

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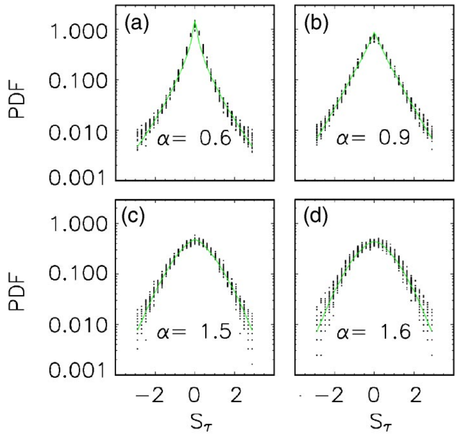

FIG. 3. (Color online). PDFs of signal differences: (a) $\tau = 0.3$ μs and (b) $\tau = 171$ μs for standard plasmas; (c, d) same τ's, but for PPCD plasmas. The dots are the PDF data and the lines are stretched exponential fits.

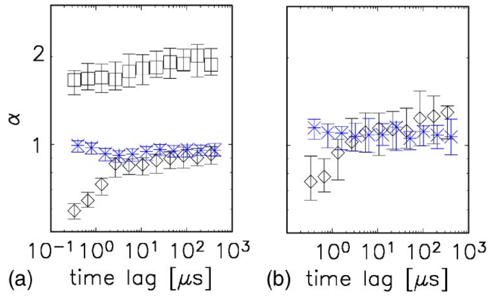

FIG. 4. (Color online). Exponents α of the PDF fitting function vs τ: (a) standard plasmas (diamonds), surrogates of standard data (stars), and PPCD plasmas (squares); (b) PDF analysis of between-sawtooth standard plasma data (diamonds), and surrogates of between-sawtooth data (stars). Autocorrelation time is 0.6–0.7 µs for standard discharges, 1.1–1.2 µs for PPCD.

ating time series in astrophysical and geophysical settings,[17] and, more recently, to magnetized laboratory plasmas.[4,5] The two techniques allow a discrimination of self-similar and intermittent features in the time series under study.

In both standard and PPCD plasmas, the PDFs of laminar times $P(\tau_L)$, calculated as in Ref. 17, are not exponential but more similar to power laws. This behavior is consistent with previous observations for electrostatic fluctuations and transport in the RFP edge[4,5,9] and in astrophysical plasmas.[17] This differs from the exponential decay typical of the classical Bak–Tang–Wiesenfeld SOC model,[6] but, as pointed out in Refs. 5 and 18, other SOC models exhibit power law decay for $P(\tau_L)$.[19]

The PDF of the signal differences at various time scales τ is defined in this case as the distribution of the time series $S_\tau(t) = \dot{b}_\phi(t) - \dot{b}_\phi(t+\tau)$, where $\dot{b}_\phi(t) = \dot{B}_\phi / \sigma_B$ is the standardized time series of nonintegrated $\dot{B}_\phi$ (i.e., with unit variance and zero mean). The PDFs is obtained by binning the $S_\tau(t)$ time series; the number of bins is a trade-off between minimization of the statistical error and accuracy of the sampling of the PDF function.[20] In pure self-similar turbulence, the PDFs at all scales collapse to a common PDF, independent of τ. This implies $\delta\dot{b}_{\gamma\tau} = \gamma^h \delta\dot{b}_\tau$ holds for a unique value of h.[21] Departures from self-similarity are highlighted by varying behavior of the PDFs at different scales τ. The PDFs are estimated using the same data as for Fig. 2. The pickup-coil signals were not analog integrated to maximize the high frequency resolution of magnetic fluctuations.

The non-self-similar character of standard plasma magnetic turbulence is revealed in the PDFs of the signal differences. Figures 3(a) and 3(b) show two PDFs: one for short time scale $\tau = 0.3$ μs and one for long time scale $\tau = 170$ μs. Obviously these have different shapes. To quantify the shape, the PDFs are fitted with stretched exponential functions $F(\delta b) = K e^{-b|\delta b|^\alpha}$ (a common procedure for this situation). Self-similar behavior is characterized by the invariance of the exponent α with varying τ, and specifically the distribution is Gaussian if $\alpha = 2$. The two PDFs of Figs. 3(a) and 3(b) have $\alpha = 0.7$ and $\alpha = 0.9$, respectively. The general trend of α versus τ is shown in Fig. 4(a) (diamond symbols), where the error bars represent the dispersion of the α distributions when the fit is performed on the PDF of a single record of the ensemble. Note that $\alpha < 1$ for small τ and increases to $\alpha \approx 1$ for larger τ. This is the same behavior as observed for the edge electrostatic turbulence measured in the reversed field experiment (RFX) (Ref. 9) and indicates that the PDFs of magnetic fluctuations are not self-similar in standard MST plasmas. The presence of tails in the PDFs at small τ indicates that larger differences occur more frequently at short time scales. This is interpreted as a signature of intermittency,[5] which is a nonlinear phenomenon related to particular phase relationships that couple different frequencies of the power spectrum. Intermittency does not occur in linear stochastic processes with random inputs, whether Gaussian or not, even if the power spectrum (or autocorrelation function) and PDF are identical to those for an intermittent process.

Therefore, a definitive test of the presence of intermittency is obtained by applying the same analysis to surrogate time series constructed from the measured $\tilde{B}_\phi$. We use the amplitude adjusted Fourier transform[22] method based on a stochastic linear model. For each record in the ensemble, a surrogate is generated with the same autocorrelation time as the original time series. The PDF of the differences at various scales is repeated, and stretched exponential fits likewise applied. No change in α with varying τ is observed in the surrogate time series [star symbols in Fig. 4(a)], i.e., no violation of self-similarity appears in the surrogates. Hence the non-self-similarity observed in the measured $\tilde{B}_\phi$ (diamond symbols) must be linked to intermittent (nonlinear) phenomena.

The intermittency observed in the edge electrostatic turbulence of standard RFP plasmas has been correlated with distinct relaxation events.[5] The data windows used in the analysis of standard plasmas described to this point in the paper include times when large sawtooth crash (relaxation) events occur. Since the sawtooth cycle in MST is regular (although aperiodic), the ensemble windowing can be performed away from the large sawtooth crashes to test explicitly a possible connection between intermittency and large relaxation events. When the above analysis is repeated, the violation of self-similarity remains, even during the rela-

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tively quiescent between-crash periods, as shown in Fig. 4(b) of α versus τ. The surrogate analysis applied to between-crash data again shows that the non-self-similarity is connected with nonlinearity in the turbulence. The origin of intermittency in the magnetic fluctuations is therefore not constrained to instants when relaxation activity is largest, but apparently also to smaller relaxation bursts occurring throughout. Examples of such smaller bursts are shown in Fig. 1(c).

In stark contrast to the above, the magnetic turbulence in PPCD plasmas is much more self-similar in nature. Figures 3(c) and 3(d) show that the PDFs of signal differences are significantly different compared to standard ones, as the tails are less important. Moreover they do not change shape significantly as τ increases: in fact the exponent $\alpha \approx 1.5$–2.0 is nearly independent of τ, as shown in Fig. 4(a) (square symbols). A robust feature of PPCD plasmas is the suppression of the large sawteeth, consistent with the PPCD goal to improve MHD stability and maintain the plasma current without dynamo relaxation. The analysis of between-crash standard plasma data described above implies the reduction in intermittency during PPCD is more than a suppression of the largest relaxation events. Apparently a greater systemic change occurs.

The spatial properties of magnetic turbulence are also substantially altered during PPCD, in particular, at high frequencies where magnetic turbulence becomes less coherent. (Most of the intermittent phenomena occur at high frequency.) The geometry of the pickup-coils permits two-point sampling of the toroidal correlation function with measurement separations $\delta x = 1$ to 5 cm in 1 cm steps. Estimates of the correlation length in the 500–600 kHz band are obtained by fitting the δx dependence of the cross-coherence γ^2 (Ref. 20) to an exponential, $\gamma^2 \propto e^{-\delta x/\lambda_{hf}}$. For these high frequencies, the correlation length $\lambda_{hf} \approx 6.5$ cm measured in standard plasmas decreases to $\lambda_{hf} \approx 3.8$ cm in PPCD plasmas. High frequency magnetic fluctuations are therefore less correlated during PPCD.

In summary, the broadband magnetic turbulence in RFP plasmas are strongly affected when the inductive parallel current drive is modified (PPCD) to induce improved MHD tearing stability. Not only are the dominant tearing modes reduced, but the fluctuations at all frequencies are greatly reduced in the bandwidth $f \leq 1.5$ MHz. The magnetic turbulence in the edge of standard RFP plasmas has statistical properties similar to those measured for the edge electrostatic turbulence and transport. The observed non-self-similarity of the PDF distributions in standard plasmas implies intermittency exists, which in previous work was correlated with dynamo magnetic relaxation events.[21] In stark contrast, the PDF distributions of magnetic turbulence in PPCD plasmas are much more self-similar. The PPCD-induced suppression of large relaxation events alone does not appear to be the essential ingredient in these changes, since analysis of between-crash data for standard plasmas (when the relaxation process is relatively quiescent) shows the same evidence for non-self-similarity and intermittency. Apparently PPCD imparts a greater systemic change, likely related to the reduction in tearing instability which provides the dominant turbulence driving force. Substantial changes in the frequency power spectra, toroidal correlation lengths and shape of the PDFs of signal differences, are other evidence of major changes. Future work should include revisiting the behavior of electrostatic turbulence and transport in a comparison of standard and PPCD plasmas.

Although the magnetic fluctuations studied in this paper do not directly represent a transport flux, a tenfold reduction in magnetic fluctuation-induced transport that accompanies PPCD (Ref. 14) suggests the magnetic turbulence characteristics observed in the edge could be reflected in transport fluxes. The level of transport achieved during PPCD is comparable to that of tokamak and stellarator plasmas,[23] so the residual turbulence during PPCD might have greater similarity to strongly magnetized toroidal plasmas (where it is observed to be self-similar in nature) than does standard RFP turbulence.

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