Intermittency in Tokamak Edge Turbulence

R. Jha, P. K. Kaw, S. K. Mattoo, C. V. S. Rao, Y. C. Saxena, and ADITYA Team[(a)]
Institute for Plasma Research, Bhat, Gandhinagar 382 424, India
(Received 5 February 1992)

We report the observation of a key feature of intermittency in the tokamak edge turbulence. The probability distribution functions of broadband plasma density and potential fluctuations in an Ohmically heated tokamak plasma are measured and shown to be non-Gaussian. The intermittency is observed on scales large compared to the dissipation scale and it is found to evolve during the flattop current phase of the discharge.

PACS numbers: 47.25.Cg, 05.40.+j, 52.55.Fa

The study of intermittency in turbulent fluids and its relation to deviations from Gaussian statistics has recently received a great deal of attention [1]. It is well known that Gaussian probability distribution functions (PDFs) naturally arise when modes with completely random phases are superposed. Near-Gaussian PDFs are adequate to describe stationary turbulent spectra such as those arising due to a cascade of energy from driven long scales to viscosity-damped dissipation scales. Most modern theories of turbulence in fluids or plasmas, therefore, use weak departure from Gaussianity outside the dissipation scale as a fundamental approximation [1,2]. Significant non-Gaussian features, measured by higher-order moments of the PDF in the spectral range outside the dissipation scale, are important quantitative measures of phase correlation amongst modes and the resulting intermittency in the turbulence [1].

In neutral fluids, the non-Gaussian nature of PDFs for velocity, velocity gradients, and passive scalars (e.g., temperature) have been observed in analytic models [1], laboratory experiments [3], and numerical simulations [4]. In contrast, there is hardly any study of intermittency in plasma turbulence [5]. In particular, although it is widely recognized that density and potential fluctuations in the tokamak edge plasma play a crucial role in determining overall confinement characteristics of the discharge, most of the experimental work on these fluctuations [6] has been devoted only to a study of correlations, spectral power indices, etc., and no measurements on intermittency have been reported. In this Letter we report what we believe are the first measurements of intermittency in tokamak edge turbulence. We demonstrate that the broadband density and potential fluctuations in the edge of the Ohmically heated ADITYA tokamak [7] exhibit non-Gaussian PDFs. It should be emphasized that although the use of simple fluid models like the Hasegawa-Mima equation or its variants [8] to describe tokamak edge turbulence has its inadequacies (difficulty of realistic modeling of wave-particle interaction effects, atomic physics phenomena—other than that through ionization and radiative loss terms, limiter boundary effects, etc.), the basic physics of non-Gaussian PDFs and their relationship to intermittency are such general features of the turbulent state that their investigation is as crucial for plasma as it is for neutral fluids.

For these experiments, ADITYA is operated at the following parameters: toroidal field $B_T=2.5$ kG; plasma current $I_p=20$ kA; major radius $R=75$ cm; minor radius $a=25$ cm; average density $\bar{n}_e=5\times10^{12}$ cm^{-3}; electron temperature $T_e\approx100$ eV. The plasma density and temperature as measured by Langmuir probes in the scrape-off layer (SOL) are 5×10^{11} cm^{-3} and ≈ 15 eV, respectively. The fluctuations in the plasma density ($\tilde{n}=\delta n_e/n_e$) and floating potential ($\tilde{\phi}=\delta\phi$) are measured using Langmuir probes separated by 5 mm from one another and distributed in the SOL and the edge region (1 to 3 cm inside the limiter) [9]. The data are digitized at 250 kHz after low-pass filtering to remove aliasing effects. Figure 1 shows plasma current, loop voltage, ion saturation current, and the SOL floating potential. The discharge typically lasts for 20–25 ms, out of which 10–15 ms is flattop in plasma current.

The wave number (k) and frequency (ω) spectra, $S(k)$ and $S(\omega)$, respectively, for $\tilde{n}$ in the SOL plasma are shown in Fig. 2 and indicate broadband turbulence. The spectra are represented by a power law with indices $\alpha_{nk}\approx\alpha_{n\omega}\approx-2$ for $k>2$ cm^{-1} and $\omega>130$ krad, respectively. The spectra for $\tilde{\phi}$ also indicate broadband turbulence and the power-law indices are $\alpha_{\phi k}\approx-4$ and $\alpha_{\phi\omega}\approx-2$ for $k>1$ cm^{-1} and $\omega>100$ krad, respectively. The statistical dispersion relation yields an average frequency $\bar{\omega}(k)$ which increases linearly with the wave number $k(\bar{\omega})$, giving an apparent phase velocity of $\approx10^5$ cm/s. The observed $E_r\times B_T$ drift speed, the phase velocity of fluctuations, and the electron diamagnetic drift speed are all of the same order of magnitude $(1\text{-}4)\times10^5$ cm/s. The statistical correlation length $l_\theta(\omega)\approx2$ to 5 cm and $l_r(\omega)\approx1$ to 3 cm. The correlation times are $\tau_\theta(k)\approx\tau_r(k)\approx5$ to 30 μs. These features are similar to the observations in other tokamaks [6].

The PDFs of density and potential fluctuations in SOL plasma are shown in Fig. 3. The density and potential data of 20 similar shots, during 8 ms of flattop in plasma current, are combined. About 40000 data points are divided into 100 bins of fluctuation amplitudes. The PDF is plotted as a function of fluctuation amplitude normalized to the standard deviation (σ) of the PDF. The dis-

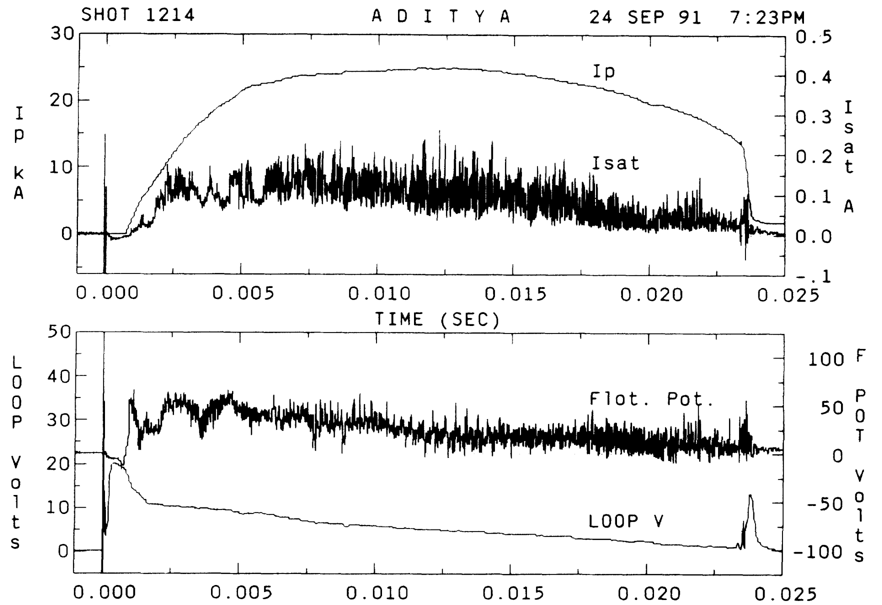

FIG. 1. Typical discharge of ADITYA. Top block: Plasma current (I_p) and ion saturation current (I_{sat}) in SOL. Bottom: Loop voltage and floating potential in SOL.

tribution functions are clearly non-Gaussian for both $\tilde{n}$ and $\tilde{\phi}$ in SOL plasma. The moments of the PDF were estimated using standard statistical procedures. The rms values of $\tilde{n}$ and the $\tilde{\phi}$ estimated from the second moments are $\sigma_n \approx 0.40$ and $\sigma_\phi \approx 7.5$ V, respectively. The values of the skewness (S) and kurtosis (K) parameters were estimated to be ≈ 2 and ≈ 20, respectively. Although the PDF showed a linear trend on a semilogarithmic plot (Fig. 3), a small number of data points ($<0.1\%$), in which the fluctuation amplitude exceeded the 6σ level, fell out of this trend. We note that the statistical errors in the PDF, beyond the 6σ level, are large because of poor statistics and may affect the estimates of the S and K parameters which are sensitive to large amplitudes. We, therefore, recalculated the moments by limiting the data points to within the 6σ level. The values of S and K, for this analysis, turned out to be ≈ 0.9 and ≈ 6, respectively. This value of K agrees with that expected for an

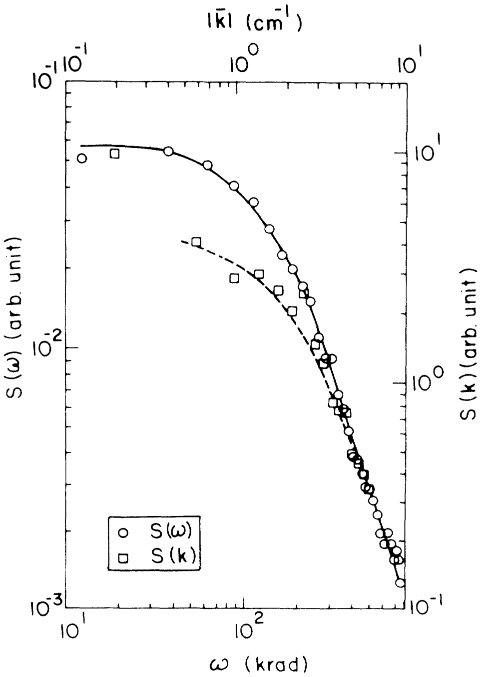

FIG. 2. $S(\omega)$ and $S(k)$ spectra for $\tilde{n}$ in SOL plasma.

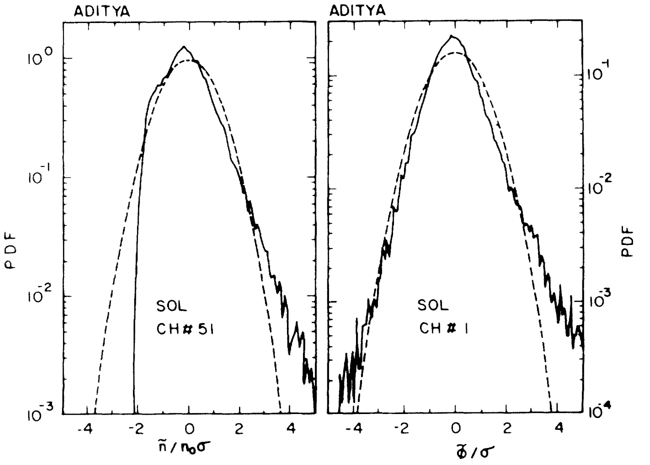

FIG. 3. The PDFs of $\tilde{n}$ and $\tilde{\phi}$ in the SOL plasma as a function of fluctuation amplitude normalized to the respective standard deviation (σ). The dashed curves represent Gaussians with the same σ.

exponential PDF. These results indicate that the observed non-Gaussian PDF is of the exponential form up to 6σ amplitudes and may exhibit a skirt at higher positive amplitudes. The negative density fluctuation (rarefaction) is limited to $|\tilde{n}| \le 1$, whereas the positive fluctuation (compression) has no such bound. Typically, the exponential tail on the positive side extends up to $\tilde{n} \approx 2$.

We have verified similar characteristics for six probes distributed in the SOL and edge plasma (1-3 cm inside the limiter) for a large number of the shots. These probes cover a range of $\tilde{n}_{\rm rms}$ values from 0.15 to 0.40, and in all these cases, the exponential and asymmetric form of the PDF persists. Thus, these characteristics are the basic features of the edge turbulence and are not determined by the probe locations or the magnitude of the fluctuations. The asymmetry of the PDF of $\tilde{n}$ indicates a preponderance of density depletions (holes) in the SOL plasma. A similar asymmetry is also seen in the PDF for the $\tilde{\phi}$.

The non-Gaussian nature of the PDFs of $\tilde{n}$ and $\tilde{\phi}$, together with their broadband spectra and short correlation time and length, is a signature of intermittency in the turbulent edge plasma of ADITYA. An interesting aspect of the present observations is that the intermittency evolves during the flattop current phase of the discharge. This is evident from the PDFs of fluctuations during two 4-ms time segments of the discharges (Fig. 4). The 8-12-ms time segment represents the initial part of the current flattop and the 12-16-ms segment represents the later part. In the first part, the PDF of the $\tilde{n}$ is Gaussian for amplitudes within the 2.5σ level ($\sigma \approx 0.33$). The deviation from Gaussian is marginal at higher positive amplitudes, while there is a sharp cutoff at $\tilde{n} \approx -1$. In the second part, the PDF is distinctly non-Gaussian. The PDF for the positive fluctuation has an exponential form up to the 5σ level ($\sigma \approx 0.51$) whereas that for the negative fluctuation shows an exponential form up to the 2σ level and then a sharp cutoff. Thus, the results indicate that the intermittency evolves during the discharge.

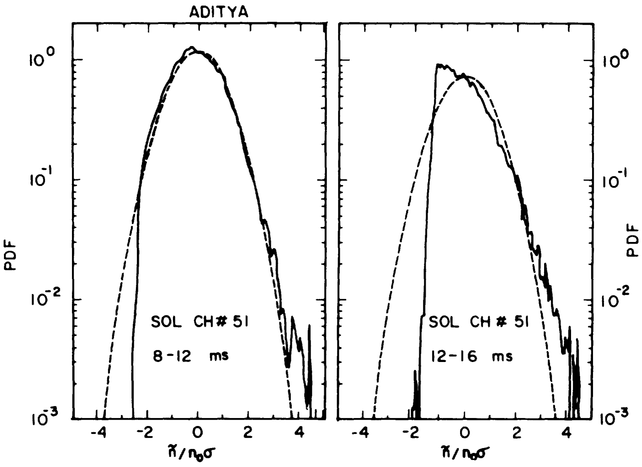

FIG. 4. The PDFs of density fluctuation as in Fig. 3. The 8-ms data are divided into two equal parts.

Since the fluctuation statistics in the dissipation range are known to be non-Gaussian, it is important to verify that our data represent scales longer than the dissipation scale. The basic dissipation mechanism in tokamak edge turbulence is parallel Landau damping (or parallel ion viscosity if the plasma is very collisional) and/or perpendicular gyroviscous damping. Unstable waves at long scales ($k_\perp \rho_i \ll 1$, $k_\parallel v_{{\rm th}i}/\omega \ll 1$) couple nonlinearly to damped short scales ($k_\perp \rho_i \approx 1$, $k_\parallel v_{{\rm th}i}/\omega \approx 1$) either directly or through the route of condensation at long wavelengths and secondary instability generation. Our measurements filter out wavelengths shorter than 1 cm (because of low-pass filtering of the data). Hence, we are outside the regime of direct gyroviscous damping. Using the experimentally measured radial decorrelation length ($\Delta r \approx 1$-3 cm) of turbulence, we find that $k_\parallel v_{{\rm th}i}/\omega \approx (k_y \Delta r/L_s) v_{{\rm th}i}/\omega \approx \Delta r\, v_{{\rm th}i}/L_s v_E \approx 0.04$-$0.12 \ll 1$ for experimental conditions in ADITYA; thus the parallel ion Landau damping is also negligible. Similarly, we conclude that the non-Gaussian characteristics of the PDFs are not due to long-lived coherent modes in the plasma because of the following: (i) The turbulence is very broadband in ω and k space; there is no distinct peak in the $S(k)$ and $S(\omega)$ spectra. (ii) The correlation times are small (5 to 30 μs).

What could be the source of the observed intermittency in the edge plasma turbulence and what would be its consequences? We now speculate on some of the interesting possibilities. It is likely that edge plasma fluctuations arise due to plasma instabilities driven by pressure gradient, current gradient, field line curvature, etc., catalyzed by radiative and ionization effects (well-known candidates are drift-dissipation modes, rippling modes, resistive ballooning modes, radiative-condensation modes, etc.). These are typically low-frequency long-wavelength ($\omega \ll \omega_{ci}$, $k_\perp \rho_i \ll 1$) instabilities for which $\mathbf{E}\times\mathbf{B}$ convection of density, pressure, and momentum is the dominant nonlinear effect. Numerical simulations of nonlinear saturation of such instabilities in $2\frac{1}{2}$ dimensions have indicated [10] a tendency towards formation of coherent long-scale-length structures. However, in a realistic 3D situation with magnetic shear, this tendency will be opposed by secondary instability processes [11] which break up the coherent structures into fine-scale eddies and put energy back into the short scale lengths where it can be dissipated. The nonlinear processes thus characteristically lead to formation of short-lived coherent structures which collapse due to secondary instabilities and lead to a new intermittent mechanism of energy dissipation which supplements the direct coupling of unstable waves to damped waves. Such processes have recently also been invoked in explaining observed intermittency in 3D hydrodynamic fluid turbulence [12]. An important consequence of the intermittency is that conventional theories

[2] of plasma turbulence which utilize a closure scheme based on weak departure from Gaussian ensemble may need serious revision. Another consequence of intermittency effects is that dissipation of plasma fluctuations and the associated anomalous transport will also exhibit an intermittent behavior. Thus, if intermittency is significant in the wavelength range which dominates the transport, the observed plasma transport will also exhibit a "bursty" character. To pin down these processes, one needs more detailed and controlled measurements on secondary instabilities, short-lived coherent structures using correlation and conditional averaging techniques [5], wavelength dependence of intermittency, characteristics of "bursty transport," effect of changing critical plasma parameters, etc. Such measurements are in progress and will be reported separately.

---

[a] P. K. Atrey, S. B. Bhatt, D. Bora, B. N. Buch, C. N. Gupta, K. K. Jain, P. I. John, A. Kumar, H. A. Pathak, H. R. Prabhakara, H. D. Pujara, K. Sathyanarayana, G. C. Sethia, A. Vardharajulu, P. Vasu, and N. Venkataramani.

[1] R. H. Kraichnan, Phys. Rev. Lett. **65**, 575 (1990); A. Pumir, B. Shraiman, and E. D. Siggia, Phys. Rev. Lett. **66**, 2984 (1991); R. Benzi *et al.*, Phys. Rev. Lett. **67**, 2299 (1991).

[2] J. A. Krommes, in *Basic Plasma Physics-II,* edited by A. A. Galeev and R. N. Sudan (North-Holland, Amsterdam, 1984).

[3] B. Castaing *et al.*, J. Fluid Mech. **204**, 1 (1989); B. Castaing, Y. Gagne, and E. J. Hopfinger, Physica (Amsterdam) **46D**, 177 (1990); Jayesh and Z. Warhaft, Phys. Rev. Lett. **67**, 3503 (1991); J. P. Gollub *et al.*, Phys. Rev. Lett. **67**, 3507 (1991).

[4] I. Hosokawa and K. Yomamoto, J. Phys. Soc. Jpn. **58**, 20 (1989); Zhen-Su She, E. Jackson, and S. A. Orszag, Nature (London) **344**, 226 (1990).

[5] T. Huld *et al.*, Phys. Fluids B **3**, 1609 (1991), and references therein.

[6] P. C. Liewer, Nucl. Fusion **25**, 543 (1985); A. J. Wootton *et al.*, Phys. Fluids B **2**, 2879 (1990).

[7] S. B. Bhatt *et al.*, Ind. J. Pure Appl. Phys. **27**, 710 (1989).

[8] A. Hasegawa, C. G. Maclennan, and Y. Kodama, Phys. Fluids **22**, 2122 (1979).

[9] In analyzing the experimental results it has been assumed that fluctuations in ion saturation current $\tilde{i} = \delta I_{\rm sat}/I_{\rm sat}$ give an accurate measure of $\tilde{n}$ and the floating potential $\tilde{\phi}$ gives a measure of the plasma potential $\tilde{\phi}_p$. Errors arising in the estimates of $\tilde{n}$ from $\tilde{i}$ due to (i) a contribution from temperature fluctuations $\tilde{T}_e$, which is not separately measured, (ii) variations in sheath thickness, and (iii) a contribution due to $\tilde{\phi}$ are estimated to be less than 10%. The error in $\tilde{\phi}_p$ due to $\tilde{T}_e$ can be substantial. In particular, this means that the non-Gaussianity of $\tilde{\phi}$ indicates that $\tilde{\phi}_p$ and/or $\tilde{T}_e$ may be non-Gaussian.

[10] S. Hamaguchi and W. Horton, Phys. Fluids B **2**, 1833 (1990), and references therein.

[11] P. K. Kaw *et al.*, "Stability of Elliptical Vortex Flows in Fusion Plasma," TCM on Research Using Small Tokamaks, Hefei, China, 3–8 October 1991 (to be published); S. C. Cowley, R. M. Kulsrud, and R. Sudan, Phys. Fluids B **3**, 2767 (1991).

[12] E. Kuznetsov, A. C. Newell, and V. E. Zakharov, Phys. Rev. Lett. **67**, 3243 (1991).