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DETECTION OF COHERENT STRUCTURES IN THE EDGE OF THE TEXT TOKAMAK PLASMA

A. V. Filippas and Ch.P. Ritz
Fusion Research Center, The University of Texas,
Austin, TX 78712

A. E. Koniges and J. A. Crotinger
Lawrence Livermore National Laboratory
Livermore, CA 94550

P. H. Diamond
Department of Physics, University of California at San Diego
La Jolla, CA 92093

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A.V. Filippas, Ch.P. Ritz
Fusion Research Center, The University of Texas,
Austin, Texas 78712, USA
A.E. Koniges, J.A. Crotinger
Lawrence Livermore National Laboratory, Livermore, CA 94550
P.H. Diamond
Department of Physics, University of California at San Diego,
La Jolla, CA 92093

Conventional plasma turbulence theories are based on the assumption of weakly interacting waves and use the random phase approximation. The fluctuation distribution in this case is quasi Gaussian and no long-lived structures, maintained through self binding forces, exist. The difficulty in identifying a turbulence model to describe the edge fluctuation characteristics in tokamaks may be a result of using such oversimplifying assumptions. Coherent structures violate these conditions. They have been found in neutral fluids and have also been studied in a cylindrical laboratory plasma.[1] In tokamaks, granular structures have been observed in the edge,[2] but no detailed statistical studies have been done so far.

In the edge of the TEXT tokamak, the probability distribution for fluctuations of the floating potential as measured by Langmuir probes, is shown in Fig. 1.a. The distribution of the potential fluctuation is close to Gaussian (solid line in the figure) with a skewness $S = \langle\tilde{\varphi}^3\rangle/[\langle\tilde{\varphi}^2\rangle]^{3/2} = -0.2 \pm 0.2$ and kurtosis $K = \langle\tilde{\varphi}^4\rangle/[\langle\tilde{\varphi}^2\rangle]^2 = 3.2 \pm 0.3$. With a conditional averaging technique[3] using higher order correlation functions, a limited set of experimental data has been analyzed in more detail. This technique can test a condition C_{cond} which is theoretically predicted to lead to long lived structures (such as a substantially negative potential dip trapping positive ions). For the simplest condition, the occurrence of a potential dip $C_{cond} = \varphi_{cond}$ at the reference point $(\vec{r}, t)$, the conditional potential at position $\vec{r} + \vec{\rho}$ and time $t + \tau$ is given by

$$\varphi(\vec{r}+\vec{\rho}, t+\tau)_{cond} = \langle \varphi(\vec{r}+\vec{\rho}, t+\tau) | \varphi(\vec{r}, t) = \varphi_{cond} \rangle \; . \tag{1}$$

A Taylor's expansion around $\varphi(\vec{r}, t)$ may be used to approximate $\varphi(\vec{r}+\vec{\rho}, t+\tau)$:

$$\hat{\varphi}(\vec{r}+\vec{\rho}, t+\tau) = \sum_{n=1}^{N} \alpha_n(\vec{\rho}, \tau)\varphi^n(\vec{r}, t) \; . \tag{2}$$

This expansion minimizes the mean square error between the estimated value (symbolized by the hat $(\hat{\,})$) and the actual (measured) value of the potential $\varphi(\vec{r}+\vec{\rho}, t+\tau)$ when the unknown coefficients, $\alpha_n(\vec{\rho}, \tau)$ satisfy a set of $m = 1, N$ equations:

$$\sum_{n=1}^{N} \alpha_n(\vec{\rho}, \tau)\langle \varphi^{m+n}(\vec{r}, t)\rangle = \langle \varphi^m(\vec{r}, t)\varphi(\vec{r}+\vec{\rho}, t+\tau)\rangle \; . \tag{3}$$

Solving the set of equations for the coefficients $\alpha_n(\vec{\rho}, \tau)$ the conditional average for the condition $\varphi(\vec{r}, t) = \varphi_{cond}$ is found:

$$\hat{\varphi}(\vec{\rho}, \tau)_{cond} = \sum_{n=1}^{N} \alpha_n(\vec{\rho}, \tau)\varphi^n_{cond} \, . \qquad (4)$$

Note that the conditional average can be estimated for several conditions, once the coefficients $\alpha_n(\vec{\rho}, \tau)$ have been computed.

In the analysis presented here, we keep terms to third order, $N = 3$. The measurements are taken during the flat top phase of the discharge, where the fluctuations are stationary, i.e. statistically independent of t. We thus take advantage of the long record length with respect to the correlation time and ensemble average over many time segments. To vary the probe separation ρ_{pol} in poloidal direction we make use of the long correlation length in toroidal direction and rotate the signal probe with respect to the reference probe on the same flux surface. The scan in ρ_{pol} is obtained over successive and similar discharges.

The structures with substantial negative excursion in the floating potential are slightly longer lived (Fig. 1.b) than the positive potential spikes (Fig. 1.c). The eddy turnover time τ_{eddy} for ions in a negative potential dip is comparable to the ambient correlation time τ_{corr} of the turbulence and slightly smaller than the lifetime τ_{life} of the structures, $\tau_{eddy} \simeq \tau_{corr} \lesssim \tau_{life}$. This is indicative of ion trapping.

To optimize the TEXT data analysis technique and to determine its sensitivity we use data generated with a numerical simulation code.[4,5] The computer code models dissipative drift wave turbulence using the model equations[6]

$$\frac{\partial}{\partial t}\nabla_\perp^2\varphi = \alpha\,(\varphi - n) + C\nabla_\perp^4\varphi \quad , \quad \frac{d}{dt}n = \alpha\,(\varphi - n) - \kappa\frac{\partial\varphi}{\partial y} \, . \qquad (5)$$

The nonlinear terms arise from the $\mathbf{E} \times \mathbf{B}$ convection as $d/dt = \partial/\partial t + \mathbf{v}_E \cdot \nabla_\perp$ and $\mathbf{v}_E \equiv \hat{\mathbf{z}} \times \nabla_\perp\varphi$. Here $\alpha = \chi_e k_\parallel^2$ is the adiabaticity parameter depending on the parallel electron conductivity, C is a damping term, and κ is an inverse scale length for the unperturbed density profile.[6] The adiabaticity parameter describes the degree of linear coupling between the density and potential equations. In the adiabatic regime ($\alpha >> 1$), the equations for n and φ are tightly coupled and the functions are virtually indistiguishable. In the hydrodynamic regime ($\alpha << 1$), the equations behave in a similar manner to two-dimensional hydrodynamic turbulence with the equation for n responding much like a passively advected scalar.

This set of equations allows a control of the coherent structures. For $\alpha << 1$ intermittent structures in density and potential are generated. For $\alpha = 0.01$ the kurtosis of potential fluctuations is $K \simeq 4.4$ and the skewness is $S = -0.1$, while $\alpha >> 1$ generates fluctuations with $K \simeq 3$, $S \simeq 0$ and no visible longlived structures. Fig. 2.a shows the motion of a few structures in the x-y plane over their life time $\tau_{life} >> \tau_{eddy}$ for a case with $\alpha = 0.01$. The probability distribution is shown in Fig. 2.b. The conditional potential of the simulation data is computed with the same technique applied to the experimental data. The result is shown in Fig. 2.c. A negative condition was used, but a positive condition gives similar results for the correlation

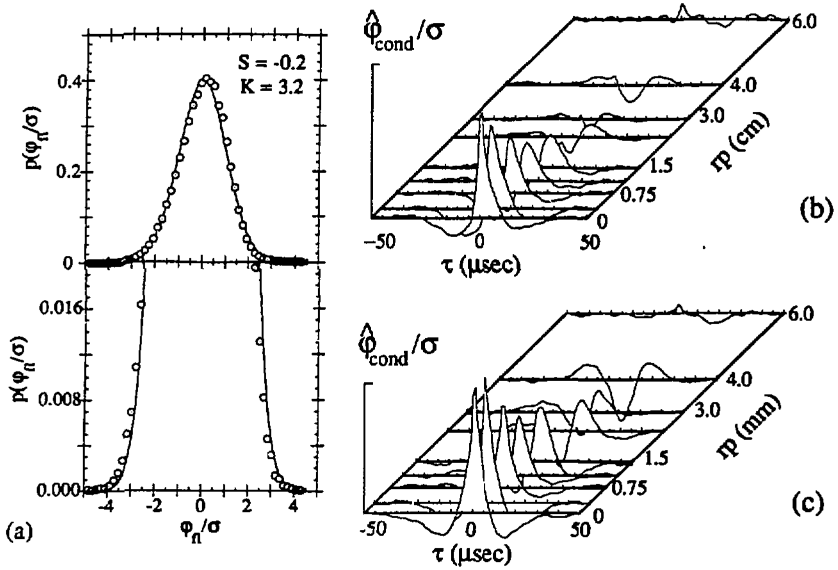

Figure 1: a) Probability distribution for measured floating potential fluctuations and conditional average for b) $\varphi_{cond} = 3\sigma$ and c) $\varphi_{cond} = -3\sigma$.

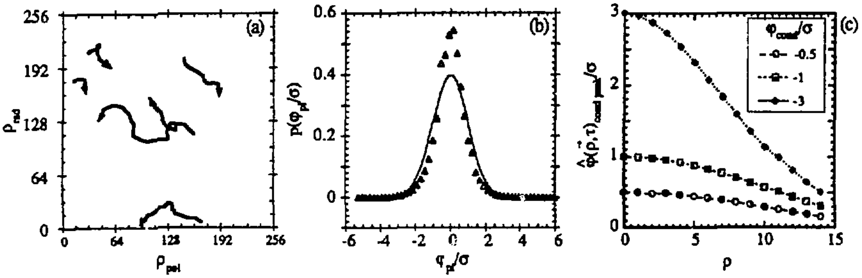

Figure 2: a) Motion of a few structures b) probability distribution and c) the spatial decorrelation of the conditional potential for three conditions φ_{cond}/σ for the numerical simulation.

length and time. This is also reflected in the symmetric probability distribution. We find the size of the structures to be well estimated, but the estimated life time $\hat{\tau}_{life}$ is much smaller than the true life time of the structures τ_{life}. The reason is the random walk of the structures (see Fig. 2.a), which is not accounted for by the simple condition which has been used in the analysis.

To summarize, we find the edge floating potential fluctuations to be close to Gaussian distributed. The conditional sampling technique shows that positive potential spikes are slightly shorter lived than negative spikes. For the negative spikes we find $\tau_{eddy} \simeq \tau_{corr} \lesssim \tau_{life}$. Present experimental data thus indicate that longer lived negative potential spikes may be present, but are probably not a dominant feature of the edge plasma of the TEXT tokamak. The analysis of the computer simulation data with known coherent structures reveals that the conditional sampling technique is capable of correctly estimating the size of the structures, but can largely underestimate their lifetime τ_{life}, because of the random motion of the coherent structures in the x-y plane. More sophisticated conditional sampling is required. Improvements in the data analysis techniques to confirm structure lifetime calculations are in progress.

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