Experimental Evidence of Three-Wave Coupling on Plasma Turbulence

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Experimental evidence of the nonlinear nature of the broadband edge fluctuations has been obtained in edge turbulence in the Advanced Toroidal Facility torsatron. Whereas little nonlinear wave interaction is found in the scrape-off layer region, three-wave coupling is enhanced in the plasma edge region ($r < a_{\rm shear}$). The degree of three-wave coupling strongly depends on the plasma conditions; it decreases in the temperature range ($T_e \approx 10$ eV) where the ionization rates depend strongly on T_e suggesting a link between ionization source and turbulence.

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Transport through broadband turbulence is an important loss mechanism for particles and energy in the plasma edge. Understanding the origin of the broadband edge fluctuations remains thus one of the key issues confronting fusion research. Many theoretical models explain the broadband fluctuation spectra on the basis of quadratically nonlinear mechanisms (i.e., three-wave interactions) which redistributes the energy supplied to the fluctuation spectrum by multiple instabilities present in the edge plasma region [1]. However, no experimental evidence of considerable wave-wave coupling of the broadband turbulence has been reported so far.

Whereas the standard linear spectral analysis (power spectrum) provides experimental information on the amplitude and phase behavior of the individual Fourier component and about the transport induced by fluctuations [2,3], it does not give any information about the coupling among different spectral components. The use of the bispectral analysis allows one to discriminate between waves spontaneously excited by the plasma and those generated by the former by nonlinear coupling [3–6]. Nonlinear mode coupling of low m modes has been recently reported in the MST reversed field pitch [7]. Coupling between long-wavelength mode and small-scale turbulence has been recently reported in the TEXT tokamak [8].

The present Letter shows the first direct evidence that quadratic interactions play an important role in the broadband edge fluctuations of a toroidal device.

The bicoherence spectrum has been computed to study the strength of the three-wave coupling contributing to the characteristics of edge fluctuations in the Advanced Toroidal Facility (ATF) ($l=2$, $M=12$ field period torsatron with $R=2.1$ m and $a=0.27$ m). Edge turbulence was studied using Langmuir probes and the experimental techniques described elsewhere [9,10]. Edge fluctuations have been characterized by the Langmuir probe ion saturation current, $I_s \approx n_e (T_e)^{1/2}$, and by the floating potential, $\phi_f = \phi_p - \alpha T_e$, where ϕ_p is the plasma potential, T_e is the electron temperature, and $\alpha \approx 3$ for hydrogen plasmas [11].

The experiments were performed in electron-cyclotron-resonance heating (ECRH) plasmas with heating power $P_{\rm ECRH} \approx 200$ kW, average electron density $\bar{n}_e \approx (4\text{–}6) \times 10^{12}$ cm^{-3}, stored energy $S_E \approx 1$ kJ, and magnetic field $B=1$ T. The signals were digitized at 1 MHz, using a 10 bit, 16 kbyte/channel digitizer. Nonlinear analysis was performed using several similar discharges to obtain more than 500 independent realizations.

The *bicoherency* is defined as

$$b^2(f_1,f_2) = B(f_1,f_2)^2 / [\langle |X_{f1} X_{f2}|^2 \rangle P(f)] , \qquad (1)$$

where $B(f_1,f_2)$ is the *bispectrum* defined as $B(f_1, f_2) = \langle X_{f1} X_{f2} X_f^* \rangle$, $P(f)$ the autopower spectrum $P(f) = \langle X_f X_f^* \rangle$, X_f is the Fourier transform of the time trace $x(t)$ and $\langle\ \rangle$ means ensemble averaging over many statistically similar realizations. The bicoherency measures the fraction of the fluctuation power at a frequency f which is phase correlated with the spectral components at frequency f_1 and f_2 obeying the summation rule $f = f_1 \pm f_2$. The bicoherency thus quantifies the degree of coupling between three waves. The bicoherency is bounded between 0 and 1: When $b^2(f_1,f_2)$ is equal to 1 then the fluctuations at frequency f are completely coupled with the frequency components at frequency f_1 and f_2 and completely uncoupled for a value of zero.

For the purpose of this Letter it is sufficient to present the *integrated bicoherency* $b^2(f) = \sum_{f1,f2} b^2(f_1,f_2)$. $b^2(f)$ represents the fraction of the total power at f which is coupled through three-wave interactions.

Figures 1(a) and 1(c) show $b^2(f)$ for measurements taken in the scrape-off layer region of the velocity shear layer ($a_{\rm shear} - r \approx -2$ cm, $a_{\rm shear}$ being the location of the

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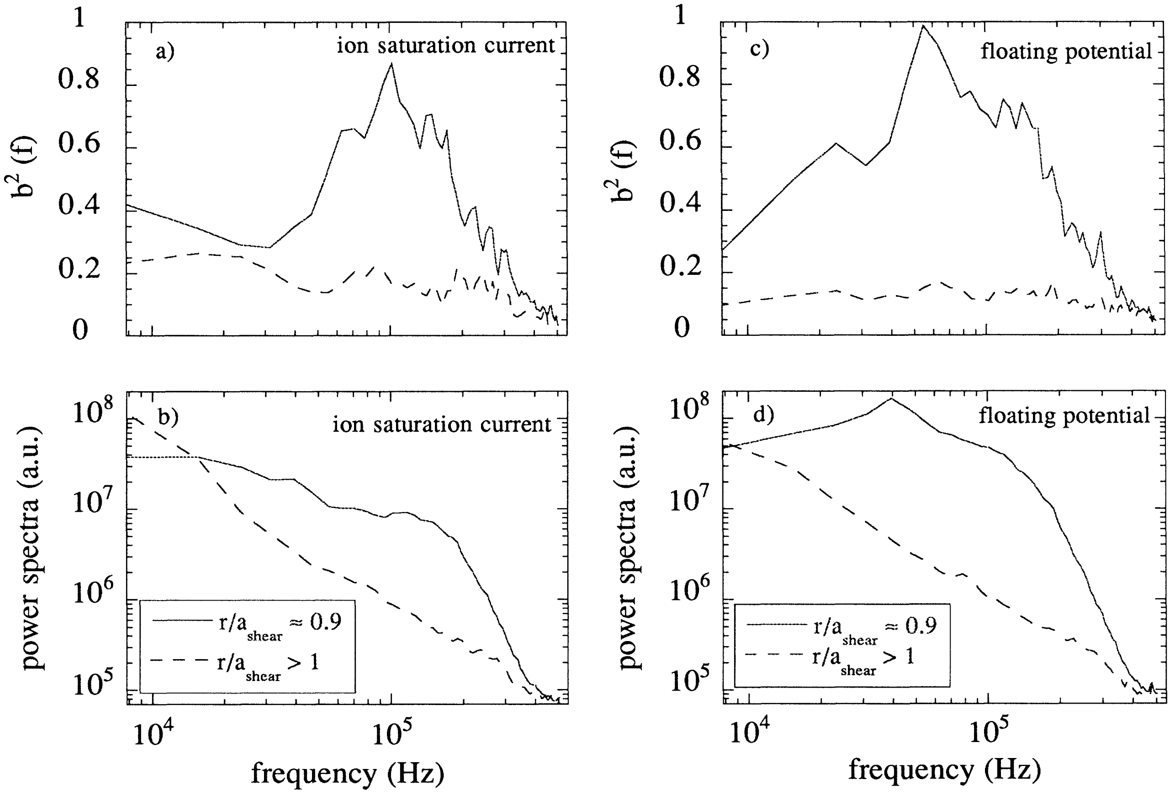

FIG. 1. Bicoherency (a),(c) and frequency spectra (b),(d) in the scrape-off layer and plasma bulk side of the velocity shear layer for ion saturation current and floating potential fluctuations.

velocity shear layer [9]) and on the plasma bulk side of the shear location ($a_{\rm shear} - r \approx 3$ cm). The corresponding frequency spectra are shown in Figs. 1(b) and 1(d) for the ion saturation current (I_s) and for the floating potential (ϕ_f) fluctuations, respectively. For the studied ECRH plasmas the degree of nonlinear coupling was found to be very similar for both signals [Figs. 1(a) and 1(c)]. This result suggests that the I_s probe induced nonlinearities are ineffective in adding to the bispectral coherence of either density or temperature fluctuations.

Whereas little quadratic interaction is found in the scrape-off layer region, three-wave coupling is enhanced in the plasma edge region ($r < a_{\rm shear}$). This coupling is very substantial in the frequency range 40-200 kHz. Note, this is also the frequency range relevant for the fluctuation induced transport [10]. The shape of the frequency spectrum is clearly modified in the range of frequencies where nonlinear mechanisms are relevant. The radial evolution of the *power weighted average bicoherency* $b^2 = \sum_f b^2(f) P(f) / \sum_f P(f)$ as well as the $\tilde{I}_s / I_s$ fluctuations are shown in the proximity of the shear layer location in Fig. 2; nonlinear mechanisms are clearly present when the shear location is passed in about 2 cm. This suggests that either the neutral source, which is large in the outer edge and in the SOL, and/or the externally imposed magnetic topology, which is complex in the far edge of torsatrons, play a key role in the turbulence process.

Note that substantial nonlinear interactions are only present when measuring further inside the bulk plasma than commonly possible with Langmuir probe measurements in tokamaks [5].

To further investigate the influence of the neutral source term on the nonlinear nature of the turbulence a neon puffing experiment has been performed. In this experiment the probe is located at a fixed radial location ($a_s - r \approx 2$ cm, a_s being the location of the magnetic separatrix) and the local electron temperature is changed by means of the gas puff. The influence of the electron temperature on the strength of the nonlinear coupling is shown in Fig. 3. With strong injection of neon impurities the edge temperature stays below 15 eV. Concurrent with this drop in T_e the nonlinear nature of the fluctuating signals disappears (i.e., b^2 drops to small values). Since the *ionization rate*, $\gamma_i = \langle \sigma v \rangle_i$, decreases rapidly when the temperature drops below 15 eV, the neutral density has gone up substantially to maintain the same local density [12]. The degree of the nonlinear coupling is not dependent on the method of edge cooling: gas puffing with the working gas (hydrogen) or impurity (neon) puffing. The role of three-wave coupling thus strongly decreases with increasing neutral source term.

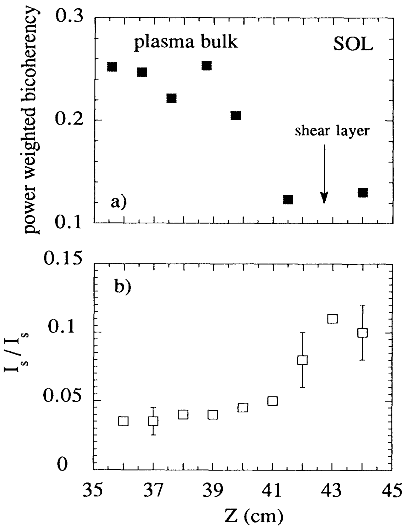

FIG. 2. (a) Power weighted bicoherency and (b) normalized ion saturation current fluctuations versus the probe position. The velocity shear layer location is at 42–43 cm. When the nonlinear wave interactions become neglectable the fluctuation level increases.

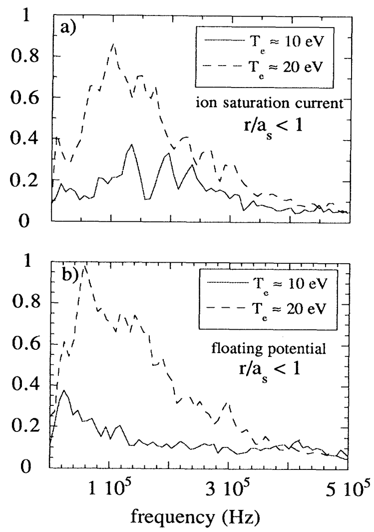

FIG. 3. Bicoherency measured at $a_s - r \approx 2$ cm at two different temperatures for (a) ion saturation current and (b) floating potential fluctuations.

Figure 4 shows the fluctuation levels and the stored energy as a function of the local electron temperature. The stored energy in the entire plasma is higher for lower fluctuation level and substantial wave-wave coupling. The level of fluctuations becomes smaller when microinstabilities are in the nonlinear regime. This is consistent with the theoretical picture predicting that the instabilities are saturated through wave-wave interactions transferring the fluctuation energy to wave-number-frequency components that dissipate the energy. The global plasma behavior is strongly affected when the edge temperature drops below 15 eV, the temperature range where γ_i decreases. Thus, the confinement properties of magnetic confined plasmas are signficantly modified by the presence of neutrals.

The present results show that in the plasma region where the neutral source term is important, the characteristics of the fluctuations are dominated by quasilinear terms. Under these conditions, fluctuations can be described in terms of many independent oscillations with frequencies in the range $f < 200$ kHz. On the contrary, in the region where the neutral concentration happens to be smaller, the characteristics of the fluctuations are dominated by nonlinear contributions. Under these circumstances, a very significant part of the frequency spectrum ($50 < f < 200$ kHz) is interlinked through some nonlinear interaction mechanism. In the plasma edge region where significant nonlinear interactions are present, the level of density fluctuations is consistent with theoretical expectations from resistive interchange modes [13]. This fact supports the validity of edge turbulence models which explain edge turbulence on the basis of quadratically nonlinear mechanisms.

The influence of neutrals on the nonlinear nature of the fluctuations could be formally explained considering that the neutral source term directly and linearly modifies the ionization term ($\gamma_i n_e$) in the electron continuity equation,

$$dn_e/dt + n_e \nabla v = \gamma_i n_e \,. \qquad (2)$$

In conclusion, the nonlinear nature of the broadband edge fluctuations has been established in edge turbulence

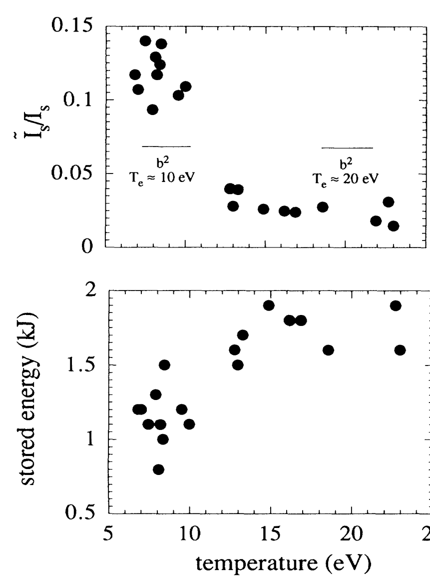

FIG. 4. Plasma stored energy and probe fluctuations versus the edge electron temperature. In the figure the temperatures at which the bispectral analysis was done are also shown (see Fig. 3).

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