Physical Mechanism behind Zonal-Flow Generation in Drift-Wave Turbulence

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(Received 18 June 2009; published 16 October 2009)

The energetic interaction between drift-wave turbulence and zonal flows is studied experimentally in two-dimensional wave number space. The kinetic energy is found to be transferred nonlocally from the drift waves to the zonal flow. This confirms the theoretical prediction that the parametric-modulational instability is the driving mechanism of zonal flows. The physical mechanism of this nonlocal energetic interaction between and zonal flows and turbulent drift-wave eddies in relation to the suppression of turbulent transport is discussed.

DOI: 10.1103/PhysRevLett.103.165004 PACS numbers: 52.30.−q, 52.35.Kt, 52.35.Mw, 52.35.Ra

Turbulence is responsible for the major part of particle and energy losses in toroidal fusion plasmas. Since the discovery of a transport barrier in 1982 [1] the reduction of turbulent transport by sheared $E \times B$ plasma flows has been intensively investigated. Of special interest is the spontaneous generation of transport barriers triggered by azimuthally symmetric, bandlike shear flows called zonal flows. In magnetized plasmas, zonal flows have the potential to improve confinement mainly due to two mechanisms: (i) the shear decorrelation mechanism [2,3] can reduce turbulent diffusive step width and (ii) the zonal flow is excited by the turbulence and thus is an energy sink for the fluctuations. Since it is impossible for zonal flows to drive radial $E \times B$ flows and, hence, turbulent transport, for the turbulence this energy is lost [2]. Zonal flows as a universal feature are also found in planetary atmospheres and in the interior of the Sun [2]. Hence, the investigation of the generation of zonal flows is also of general interest in physics.

The interaction between turbulence and zonal flows has been studied in many experiments ([4] and references therein). Especially, the nonlinear drive of shear flows by Reynolds stress has been demonstrated in the linear device CSDX [5] and the reversed field pinch RFX [6]. Theory predicts that zonal flows are driven nonlocally in k space by the parametric-modulational instability [2]. For an experimental verification of the modulational instability as the zonal-flow driving mechanism a scale resolved analysis is required. To achieve this, usually, a bicoherence analysis is carried out in frequency space. Thus, a nonlocal coupling between turbulence and zonal flows, including the geodesic acoustic mode (GAM), has been demonstrated, e.g., in Refs. [7–12]. The GAM is a finite frequency zonal flow. However, a bicoherence analysis yields information on the degree of phase locking of different modes only and, thus, identifies modes that can couple with each other. Driving or damping of zonal flows and the relative importance of the various interactions can only be estimated from an energy transfer analysis. Energy transfer studies of the turbulence-zonal-flow interaction and the turbulent cascades have been carried out [13–17]. These studies were done in frequency space, too, using Taylor hypothesis to transform the fluctuations from frequency to k space. Furthermore, the analyses were done in one dimension only. The physical processes, however, take place in the two-dimensional wave number space [18].

This article addresses the nonlinear energy transfer between drift-wave turbulence and zonal flows in 2D k space directly. The experimental observations contribute to the understanding of both zonal-flow generation and turbulence suppression. In a previous analysis [19] the turbulent inverse cascade was investigated. The analysis revealed the importance of nonlocal energy transfer for the inverse cascading process. This work extends the validity of the previous result to the nonlocal turbulent drive of zonal flows. The consequences of this result for turbulence suppression will be discussed.

Experiments have been carried out on the stellarator experiment TJ-K, which confines a low-temperature plasma with dimensionless parameters similar to those in fusion edge plasmas [20]. The major and minor radii are $R_0 = 0.6$ m and $a = 0.1$ m, respectively. The working gas was helium at a neutral gas pressure of $p = 7$ mPa. The plasma had a line-averaged density of about $\bar{n} = 10^{17}$ m^{-3} and was generated by microwaves at a frequency of 2.45 GHz and a power of 1.8 kW at a magnetic field strength of $B = 72$ mT. The electron temperature was about $T_e = 9$ eV and the ion temperature less than 1 eV. The moderate temperatures allowed for measurements of long time series (1 s at 1 MHz) with an array of 128 Langmuir probes arranged on four neighboring flux surfaces. Therefore, 32 Langmuir probes were positioned on each of the four flux surfaces. The poloidal and radial probe distances were 1.5 and 0.5 cm, respectively. Details on the diagnostics can be also found in Ref. [21]. The floating potential fluctuations are interpreted as plasma potential fluctuations $\tilde{\phi}$, which has been shown to be valid for TJ-K plasmas [22]. The measured potential fluctuations are normalized to the electron temperature, $\phi = e\tilde{\phi}/T_e$. Measured ion-saturation current fluctuations are interpreted as density fluctuations $\tilde{n}$ and are normalized to the background ion-saturation current, $n = \tilde{n}/n_0$. All lengths are normalized to the drift-scale parameter or hybrid Larmor radius $\rho_s = \sqrt{(m_i T_e)}/(eB) \approx 1.2$ cm, with m_i the ion mass and e the elementary charge.

The data from the 2D probe array were analyzed in k space directly. The energy transfer was calculated using the technique by Camargo *et al.*, which has been developed for the analysis of drift-wave turbulence based on the Hasegawa-Wakatani equations [23]. The use of the Camargo method should be justified, since in many experiments it has been well established that turbulence in TJ-K is dominated by drift waves [20,24,25], Previously, the method has been tested successfully on Hasegawa-Wakatani simulations and it was used for the investigation of the dual cascade on TJ-K [19]. A discussion of the applicability of this method for TJ-K plasmas can be found in Ref. [19]. In the following, the transfer of the fluid kinetic energy $E^V(\mathbf{k}) = 1/2|\mathbf{k}\phi_\mathbf{k}|^2$, the density fluctuation activity $E^N(\mathbf{k}) = 1/2|n_\mathbf{k}|^2$, and the mean squared vorticity $E^W(\mathbf{k}) = 1/2|k^2\phi_\mathbf{k}|^2$ will be calculated. The spectral transfer $T(\mathbf{k} \leftarrow \mathbf{k_1})$ of these quantities from mode $\mathbf{k_1}$ to mode $\mathbf{k}$ is given by the following expressions [19,23]:

$$T^V(\mathbf{k} \leftarrow \mathbf{k_1}) = -2(k_r k_{\theta 1} - k_{r1} k_\theta) k_2^2 \mathrm{Re}\langle \phi_\mathbf{k}^* \phi_{\mathbf{k_2}} \phi_{\mathbf{k_1}} \rangle, \tag{1}$$

$$T^N(\mathbf{k} \leftarrow \mathbf{k_1}) = -2(k_r k_{\theta 1} - k_{r1} k_\theta) \mathrm{Re}\langle n_\mathbf{k}^* \phi_{\mathbf{k_2}} n_{\mathbf{k_1}} \rangle, \tag{2}$$

$$T^W(\mathbf{k} \leftarrow \mathbf{k_1}) = 2(k_r k_{\theta 1} - k_{r1} k_\theta) k^2 k_1^2 \mathrm{Re}\langle \phi_\mathbf{k}^* \phi_{\mathbf{k_2}} \phi_{\mathbf{k_1}} \rangle. \tag{3}$$

Here $\langle \cdot \rangle$ denotes the ensemble average taken as a time average. The asterisk denotes the complex conjugate and Re the real part of a complex number. The common factor $k_r k_{\theta 1} - k_{r1} k_\theta$ is intrinsically two dimensional (r and θ denote the radial and poloidal directions, respectively) and follows from the nonlinearities of the system. Thus, a two-dimensional treatment of the energy transfer is essential and a 1D adaptation must be interpreted with great caution. The multiprobe array enables a two-dimensional treatment of the nonlinear behavior with high poloidal resolution $k_\theta \in \{-16, \ldots, 16\}(2\pi/(32 \times 0.015\rho_s))$, whereas the radial resolution is poor $k_r \in \{-2, -1, 1, 2\}(2\pi/(32 \times 0.005\rho_s))$.

Figure 1 shows the result of the analysis of the fluid kinetic energy transfer function. $T^V(\mathbf{k} \leftarrow \mathbf{k_1})$ forms a four-dimensional quantity depending on $(k_{r1}, k_{\theta 1}, k_{r2}, k_{\theta 2})$, with the constraint $\mathbf{k} = \mathbf{k_1} + \mathbf{k}_2$. Hence, for a graphical representation, sums of all contributions (k_r, k_{r1}, $k_{r2} \neq 0$) at given $k_{\theta 1}$ and $k_{\theta 2}$ have been taken and divided by the number of contributions. For the interpretation of this type of representation see also Ref. [26]. In addition the total transfer function $T_{\mathrm{tot}}^V(k_\theta) = \sum_{k_{\theta 1}} T^V$ is included into the figure. The curve is a projection of the 2D data on the $k_\theta = k_{\theta 1} + k_{\theta 2}$ axis. The vertical line in the total transfer function figure is the zero transfer line. First concentrate on the $k_\theta = 0$ contribution, which can be put on a par with the zonal flow, since only contributions with finite $k_r \neq 0$ have been considered. Contributions coupling into $k_\theta = 0$ are found on the diagonal line with $k_{\theta 1} = -k_{\theta 2}$. One clearly observes a coupling of the zonal flow ($k_\theta = 0$) with the drift-wave modes ($k_{\theta 1} \neq 0$). In the 2D plot, a small energy transfer from $k_\theta = 0$ (corresponding to a poloidal mode number of $m = 0$) to $k_{\theta 1} = 0.2$ (poloidal mode number $m = 1$) is visible. This could indicate the energy transfer from the zonal flow into the GAM. Theoretically, this is the channel through which GAMs can be driven [18,27,28]. All other modes couple energy to the zonal flow. The energy transfer function T_{tot}^V at $k_\theta = 0$ is strongly positive, which represents a net energy transfer from the drift-wave turbulence to the zonal flow. One sees that the energy transfer to the zonal flow comes predominantly from smaller scales ($k_{\theta_1} \gtrsim 1$). Thus, the energy transfer is mostly nonlocal. This confirms the theoretical prediction that the parametric-modulational instability is the driving mechanism of zonal flows.

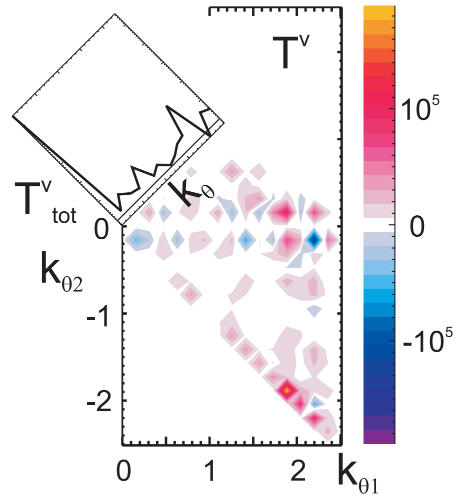

FIG. 1 (color online). Nonlinear fluid kinetic energy transfer.

In addition, the spectral transfer functions of the density fluctuation activity and the mean squared vorticity have been evaluated. To this end, potential and density fluctuations were measured simultaneously on alternating probe tips. This reduces the spatial resolution of the probe array by a factor of 2. In Fig. 2, the results for all energy transfer channels are shown at the reduced resolution. The energy transfer from the smaller scales, which in Fig. 1 was found to be dominant, cannot be resolved anymore at this resolution. However, the basic result, namely, the energy transfer from turbulence into the zonal flow, can be demonstrated at this resolution, too. As expected from a comparison of Eq. (1) with Eq. (3), the enstrophy transfer T^W shown in Fig. 2(c) is into the opposite direction of that of T^V and is weighted by k^2. The density fluctuation

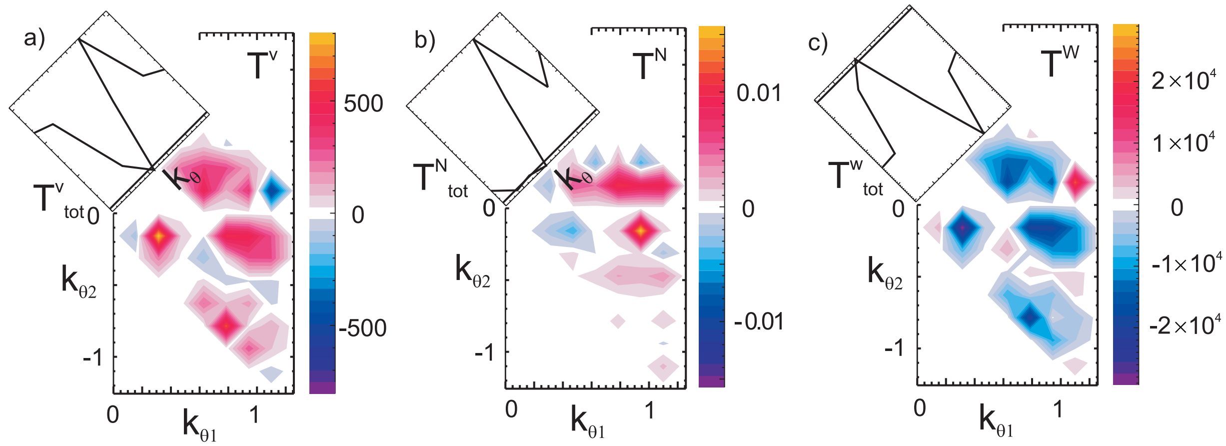

FIG. 2 (color online). (a) Nonlinear fluid kinetic energy transfer, (b) nonlinear density fluctuation activity transfer, and (c) nonlinear fluid enstrophy transfer. Note that the resolution is only half of the one in Fig. 1.

activity T^N [Fig. 2(b)] shows no significant transfer between turbulence and fluctuations with $m = 1$ ($k_\theta = 0.2$). $m = 1$ density fluctuations would be a signature of a GAM. Hence, this finding is consistent with the theoretical expectation [18] that GAMs tap their energy from the zonal flow and not from broadband turbulence.

The experimental findings from above are now interpreted with the help of Fig. 3. It sketches the temporal evolution of eddies embedded in a large-scale strain field as from the zonal-flow vorticity. The two figures differ mainly in the third time step. In the second step [Figs. 3(b) and 3(d)] due to the flow shear the eddy will be tilted and elongated [29]. Since the circulation of an eddy is conserved, the velocity around the eddy is lowered and its energy is reduced [30,31]. At the same time, the velocity of the eddy is now mainly directed such that it reinforces the large-scale strain [30,31]. Thus energy is transferred from the eddy to the zonal flow by an elongation and tilting (and thinning) of the eddy. This process is most effective if the scale of the interacting flows is clearly different, as in the case of zonal flows and small-scale vortices. A large-scale eddy has a stronger vorticity and can persist unmodified (or "unmodulated") [32]. This is the reason why the energy transfer to the zonal flow (but also in the inverse cascade [19,30,31]) is highly nonlocal as confirmed by the present analysis.

Finally, the meaning of the energy transfer for the reduction of turbulent transport is addressed. Since the tilting-stretching mechanism transfers energy to the zonal flow, the energy in the turbulence is reduced, which should lead to reduced fluctuations amplitudes and transport. In fusion research it is widely assumed that the eddies are stretched and finally torn apart by the shear flow as shown in Fig. 3(c). The breaking up of eddies does not cause further energy transfer to the zonal flow, but it reduces the step size of turbulent diffusion and therefore should reduce transport.

In fluid turbulence it is observed, however, that instead of breaking apart smaller eddies are further elongated and coiled up by the larger flow [29,33,34]. The elongated eddies are finally destroyed by a straining-out process [33,34]. This corresponds to the illustration in Figs. 3(d)–3(f). In this process the entire energy of the eddy can be transferred to the zonal flow and additional energy is taken out of the fluctuations driving turbulent transport. This mechanism is directly related to the generation process of the zonal flows. The fact that in experi-

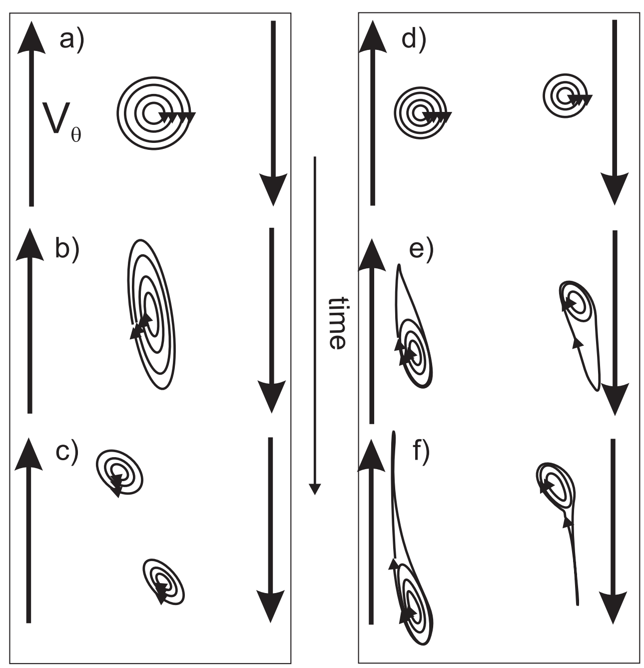

FIG. 3. Artist's view of the zonal-flow generation and accompanied turbulence decorrelation. (a)–(c) The common decorrelation mechanism: the eddies are torn apart. (d)–(f) Vortex thinning mechanism: the eddies are taken over by the zonal flow.

ments in general the breaking up of eddies is not observed, supports the argument that energy transfer by tilting and straining out of the small-scale eddies is the main cause for the reduction of turbulent transport.

In summary, the energy transfer between drift waves and zonal flows has been investigated experimentally in a toroidally confined low-temperature plasma using an extensive 2D probe array. The energy transfer from turbulence to the zonal flow has been analyzed directly in wave number space. It has been shown that the energy transfer is highly nonlocal. This nonlocality provides an experimental evidence of the parametric-modulational instability, which is inherently nonlocal in k space, as the main driving mechanism of zonal flows by a turbulent drift-wave spectrum. In particular, the energy transfer to the zonal flow is found to be predominantly from the small scales. The physical mechanism of the zonal-flow drive consistent with this observation is an elongation and tilting of small eddies by the zonal flow.

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