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Non-diffusive transport caused by low-frequency vortex-like turbulence in magnetized plasmas with sheared flows.

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Introduction.

Low-frequency (LF) turbulence and the resulting anomalous cross-field plasma transport observed in various magnetic systems with different magnetic field topologies and plasma parameters show rather common features including formation of large-scale vortex-like structures and non-diffusive fluxes of particles and energy. Theory and experiments give evidences that LF turbulence in magnetized plasmas tends to be two-dimensional (2D) or quasi-two-dimensional. Both direct and inverse cascade processes are responsible for the formation of dominant vortex structures and nonlinear spectra in such turbulence. As a result, the dominant structures are relatively independent on spatial scales of initial linear instabilities, have a tendency to enlarge their own spatial scales, and cause the intermittent non-diffusive cross-field plasma transport. Our previous analysis [1-3] has shown that the direct modeling of the nonlinear LF plasma dynamics is a very promising approach to the theoretical study of such turbulence. Closed set of adiabatically reduced weakly dissipative MHD-like equations is used to describe both the low-frequency turbulent plasma dynamics and the resulting non-diffusive transport processes. Here we present results of such simulations based on an advanced set of reduced MHD-like equations obtained in [4].

Theoretical model.

New set of reduced equations obtained in [4] allows us to simulate the LF turbulent dynamics and plasma transport in a wide class of plasma confinement systems with closed and open magnetic field-lines including systems with high field-line curvature such as levitated dipole and non-papaxial mirror-based systems. Partially, the results of simulations can be applied to analyze tokamak experiments as well. The basic element of the reduced equations is the adiabatic velocity field $\mathbf{v}_a$ that does not perturb fast stable collective degrees of freedom and describes the relatively slow (reduced) dynamics of the system:

$$\mathbf{v}_a = \frac{1}{B^2}[\mathbf{B} \times \nabla\Phi(t, \psi, \varphi)] + \mathbf{B}\,\lambda\,\partial_\varphi\Phi(t, \psi, \varphi)\,, \qquad (1)$$

where factor λ is determined in [4] and describes a longitudinal redistribution of plasma pressure and density in non-uniform magnetic field. It is important that 3D velocity field $\mathbf{v}_a$

is completely described by only one scalar potential function $\Phi(t, \psi, \varphi)$, which is 2D-function in terms of poloidal magnetic flux ψ and toroidal angle φ.

Functional structure of the adiabatic velocity field prescribes the form of reduced equation of motion, which has to be written for a quantity $\hat{w}\,(t, \psi, \varphi)$, which can be called as the dynamic vorticity of plasma in magnetic flux-tube [4]. This quantity is the canonical momentum of the reduced adiabatic plasma motion and has the form:

$$\hat{w} = \partial_\psi \left(\hat{\rho}\,\langle r^2\rangle\,\partial_\psi\Phi\right) + \partial_\varphi \left(\hat{\rho}\,\langle r^{-2}B^{-2} + \lambda^2 B^2\rangle\,\partial_\varphi\Phi\right), \tag{2}$$

where r is the distance from the axis of system symmetry, symbol $\langle\ldots\rangle$ denotes averaging over specific flux-tube volume U and $\hat{\rho}$ is the plasma mass within the volume U. The reduced equation of motion obtained in [4] is an exact consequence of initial equation of motion and can be presented in the following form:

$$\partial_t\big|_\psi\,\hat{w} + [\Phi,\,\hat{w}] - \frac{1}{2}[\hat{\rho},\,\langle v_a^2\rangle] + \partial_\psi U\,\partial_\varphi\langle p\rangle = \{DT\}, \tag{3}$$

$$[\Phi,\,\hat{w}] \equiv \partial_\psi\Phi\,\partial_\varphi\hat{w} - \partial_\varphi\Phi\,\partial_\psi\hat{w},$$

where symbol {DT} on the right-hand side denotes "dissipative terms" related to viscosity and external sources of momentum. Additionally, the main force balance takes the form of Grad-Shafranov equation and accounts quasi-equilibrium φ-uniform pressure component $p_0(t, \psi)$. The corresponding reduced equations for density and heat transfer takes the form:

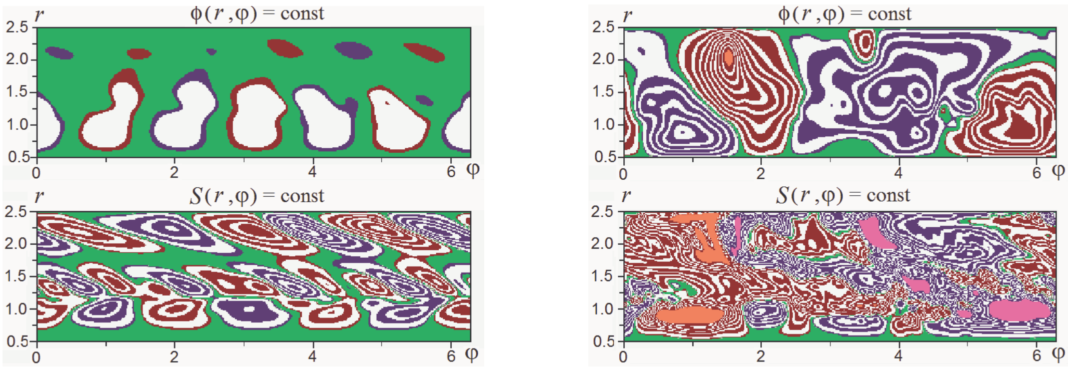
$$\partial_t\big|_\psi\,\hat{\rho} + [\Phi,\,\hat{\rho}] = \{DT\}_\rho, \qquad \partial_t\big|_\psi\,S + [\Phi,\,S] = \{DT\}_S, \tag{4}$$

where $S = pU^\gamma$ is a single-valued function of plasma entropy in the volume U, and symbols $\{DT\}_\rho$ and $\{DT\}_S$ denote "dissipative terms" those describe the classical (neoclassical) plasma diffusion and thermal conduction, as well as sources of energy and particles. φ-averaged components of Eqs. (3, 4) define sheared flow fluctuations (zonal flows) and evolutions of quasi-equilibrium density and entropy components. See Ref. [3, 4] for details.

Computer simulation of LF turbulent plasma dynamics and transport.

Previously [1-3], computer simulations of long-term turbulent evolutions at the time scales exceeding plasma lifetime have shown formation of self-consistent pressure and density profiles, L-H transitions with appropriate transient times, non-Gaussian statistic of fluctuations and other features observed in various plasma confinement experiments.

Our recent results show that effect of sheared flows is a complex nonlinear phenomenon, which cannot be described in terms of linear stability theory only. Fig. 1 illustrates influence of sheared flows with rather high integral vorticity (W_I=*10*). The turbulence is self-consistently maintained by pressure-driven instability in a simplified levitated dipole configuration. Equipotential curves $\phi(r, \varphi)$ = const correspond to vortex flow lines. Curves $S(r, \varphi)$ = const illustrate structure of entropy fluctuations. Initial radial profile of sheared flow vorticity $w_0(r)$ was picked at minor radius $r = 1.75$. Then the profile evolves under the self-consistent but uncontrolled influence of the turbulence. Fig. 1a illustrates an early stage of turbulent evolution, at which turbulence has a reduced level in comparison with those in low-vorticity regimes. Nevertheless, later the turbulence forms well-developed vortex-like structures (Fig. 1b), which are similar to those in low-vorticity regimes and results in a flattening of $w_0(r)$ profile.



a) b)

Fig. 1. 2D turbulent structures in levitated dipole system with external divertor separatrix in presence of sheared flows with uncontrolled vorticity: a) initial stage (t=8.5) of partially suppressed turbulence; b) stage of well-developed turbulence (t=28.0).

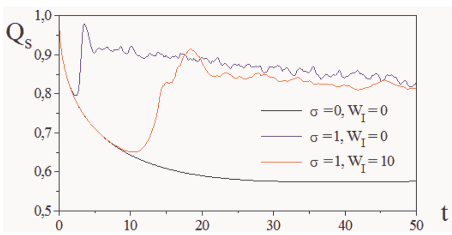


Fig. 2. Heat fluxes through the separatrix in regimes with low (W_I=0) and high (W_I=10) integral vorticities. Black curve presents regime without turbulence.

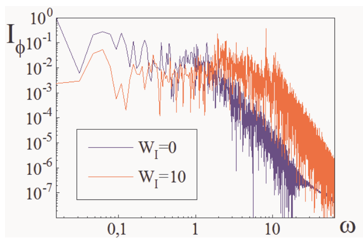


Fig. 3. Frequency spectra of potential fluctuations in regimes with low (W_I=0) and high (W_I=10) integral vorticities.

Fig. 2 shows that the reduced level of turbulence at the initial stage of high-vorticity regime results in almost classical heat flux. However, later the flux rises to anomalous level that is comparable with the flux level in low-vorticity regime. Fig. 3 shows that frequency spectra of potential fluctuations consist of broadband and sharp picks in the both regimes.

Fig. 4 illustrates pressure-driven turbulence in highly non-paraxial mirror-based configuration with divertor-like separatrix at the edge. Fig. 4a presents initial radial profiles of main plasma parameters including strong sheared plasma rotation (mainly clockwise). Initial pressure profile is marginally stable with respect to the flute-like pressure-driven instability ($S_0(r)$ = const). Qualitatively, turbulent evolution in this case is similar to that illustrated by Fig. 1. Fig. 4b illustrates a reduced level of turbulence at the early stage of evolution. Fig. 4c illustrates well-developed turbulent structures in regime with uncontrolled vorticity. Hot (red) blob at the plot $S(r, \varphi)$ = const is very similar to that observed by means of soft X-ray tomography in GAMMA 10 experiments [5]. Fig. 4d illustrates regime, which has the same plasma parameters and initial conditions as regime illustrated by Fig. 4c. However, profile of sheared rotation in this regime is controlled by a source of momentum, which forms a layer with high vorticity localized near $r = 0.6$. Existence of such layer causes a decoupling of vortex structures localized in inner and outer plasma regions and results in formation of transport barrier in the vicinity of the layer.

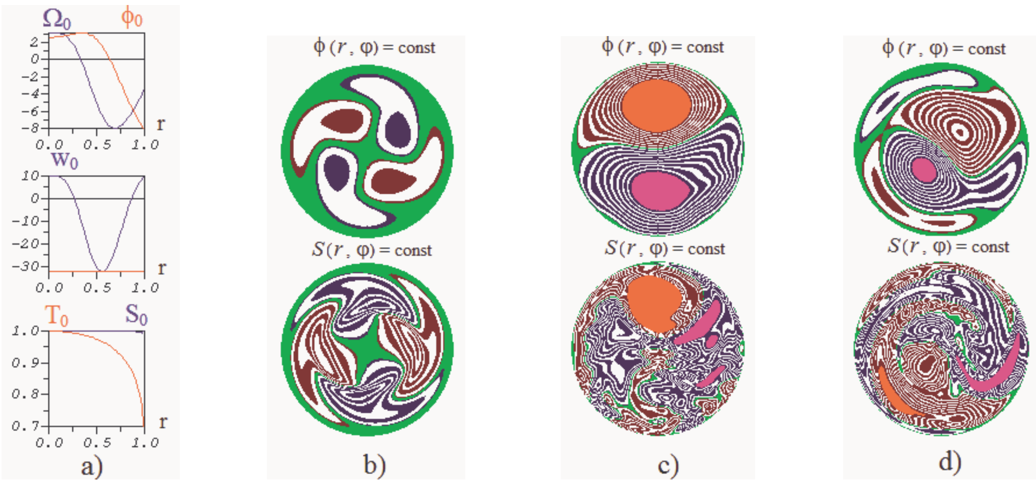


Fig. 4. 2D turbulent structures in tandem mirror central cell with divertor separatrix: a) initial radial profiles of plasma potential ϕ_0, frequency of sheared rotation Ω_0, dynamic vorticity of sheared rotation w_0, temperature T_0, and entropy function S_0; b) initial stage (t=10.0); c) well-developed turbulence with uncontrolled vorticity; d) well-developed turbulence with vorticity controlled by momentum source.

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