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Dynamic Response of Gradient and Turbulent Transport in Resistive Ballooning Turbulence

抵抗性バルーニング乱流における勾配・輸送の動的応答

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The flux-driven nonlinear simulation of resistive ballooning mode with tokamak edge geometry is performed. In the situation with the poloidal rotation is artificially suppressed, the radial propagation of pulses of pressure gradient is observed. It is found that the fluctuation with higher mode number propagates with the pulse. Statistical values of the pulses propagation are evaluated. The scale length and propagation velocity are compared with theoretical estimations and it gives good agreement.

1. Introduction

Recent experimental study reveals that fluctuations with the long-range radial correlation exist in fusion experimental device and their spatiotemporal structure is characterized by the ballistic radial propagation [1]. Ballistic propagation is considered to play an important role in determining the turbulent transport in fusion experimental devices such as ITER and DEMO. Ballistic behaviors and dynamics have been studied widely [2]. However, the statistical characteristics have not been discussed enough. In this presentation, we report statistical characteristics of ballistic radial propagation of pulses of pressure gradient using the global nonlinear simulation. They are compared with theoretical estimation and give good agreement.

2. Model and Simulation Conditions

The two-field reduced-RBM (Resistive Ballooning Mode) equations are solved to reproduce the plasma edge turbulence in the tokamak geometry [3]. The following equations are employed for the normalized electrostatic potential ϕ and pressure p.

$$\frac{\partial}{\partial t}\nabla_\perp^2\phi + \left[\phi, \nabla_\perp^2\phi\right] = -\nabla_\parallel^2\phi - \mathbf{G}p + \mu\nabla_\perp^4\phi, \qquad (1)$$

$$\frac{\partial p}{\partial t} + [\phi, p] = \epsilon_c\mathbf{G}\phi + \chi_\parallel\nabla_\parallel^2 p + \chi_\perp\nabla_\perp^2 p + S(r), \qquad (2)$$

The notations and symbols are explained as follows. $\nabla_\parallel$ and $\nabla_\perp$ are gradient parallel and perpendicular to the magnetic field line. $[f,g] = (\partial f/\partial x)(\partial g/\partial y) - (\partial f/\partial y)(\partial g/\partial x)$ is the Poisson bracket. The curvature operator $\mathbf{G}$ is introduced. μ indicates the collisional viscosity, $\chi_\parallel$ and $\chi_\perp$ are parallel and perpendicular collisional heat diffusivities. $\epsilon_c = 2\Gamma(L_p/R_0)$ is the parameter that is related to a curvature coefficient, where $\Gamma = 5/3$ is the adiabatic index, L_p is the scale length of the pressure gradient and R_0 is the major radius at the reference surface. In this RBM model, the diamagnetic velocity is neglected in comparison with the ExB velocity, and the parallel current is evaluated by using a simplified electrostatic Ohm's law, $\eta_{\parallel 0} j_{\parallel} = -\nabla_{\parallel}\phi$, where $\eta_{\parallel 0}$ is a reference value of the parallel resistivity and $j_{\parallel}$ is the parallel current. The system is normalized using the resistive interchange time $\tau_{\mathrm{int}}^2 = R_0 L_p / \left(2c_{s0}^2\right)$ in the time, resistive ballooning length $\xi_{\mathrm{bal}}^2 = m_i n_0 \eta_{\parallel 0} L_s^2 / \left(\tau_{\mathrm{int}} B_0^2\right)$ in the perpendicular length, and magnetic shear length L_s in the parallel length, where $c_{s0} = \left(p_0 / \left(n_0 m_i\right)\right)^{1/2}$ is the reference sound speed. p_0, n_0, and B_0 are reference values of the pressure , density and magnetic field, respectively. m_i is the ion mass.

The model equations are solved numerically by a finite difference method in the radial direction and by a Fourier expansion in the poloidal and toroidal directions. The maximum radial grid number is 104, the maximum toroidal mode number is 32, and the maximum poloidal mode number is 112. To save calculation time, only one in four toroidal modes is included in the simulations. In the (m,n) space, the $(n=0, m>0)$ modes are suppressed to keep the neoclassical terms consistent (especially for the $(1,0)$ mode), where m is the poloidal mode number and n is the toroidal mode number, respectively. By assuming the safety factor $q(r)$ is monotonically increasing, the simulation domain covers a region between $q = 2.5$ and $q = 3.5$. The regions $q < 2.5$ and $q > 3.5$ are used for a dumping buffer. In the dumping buffer region, the dissipation rate is set to be large. In the simulation region, the ion viscosity μ and the diffusivity $\chi_{\perp}$ are set to be 0.93. The parallel diffusivity is $\chi_{\parallel} = 0.5$ and $\epsilon_c = 0.04$. A Gaussian type pressure source is introduced in the inner buffer region, i.e., $q \le 2.5$. We vary the amplitude of the pressure source $S(r)$ in the simulations. The simulations are performed in the situation that the poloidal rotation velocity is always suppressed artificially.

3. Simulation Results

Flux-driven Nonlinear simulations for edge turbulence are performed. It is found that the coexistence of the radial propagation of the pulse of pressure gradient and the appearance/disappearance of the radial global structure of heat flux in nonlinearly saturation phase. Here, we focus on the pulse propagation. The pulses of pressure gradient propagate radially outward and inward. It is found that the propagation front is a boundary of the fluctuation with higher poloidal mode number and that with lower poloidal mode number. When the pulse of pressure gradient propagates outward, the propagation of fluctuation with higher poloidal mode number is also observed. The details of pulse propagation are statistically analyzed for three different input energy sources S. The scale length of the pulse l, averaged velocity of the pulse v, and effective diffusion coefficient D_{eff} are evaluated, where the scale length is calculated from the curvature of the peak of the auto-correlation and the effective diffusion coefficient is evaluated by $D_{\mathrm{eff}} = \langle \Gamma \rangle / \langle \nabla p \rangle$, where Γ indicates heat flux and $\langle\ \rangle$ indicates spatial and temporal average. The spatial scale length l is compared with the theoretical estimation $\left(D_{\mathrm{eff}} / \gamma\right)^{1/2}$ [4], where γ is the linear growth rate and the order of magnitude agrees. The velocity of pulse v is compared with the estimation $\left(D_{\mathrm{eff}} \gamma\right)^{1/2}$ [4] and the order and tendency agree.

4. Summary

The flux-driven nonlinear simulation of resistive ballooning mode with tokamak edge geometry is performed. In the situation with poloidal rotation is artificially suppressed, the radial propagation of pulses of pressure gradient is observed. It is found that the fluctuation with higher mode number propagates with the pulse. Statistical values of the pulses propagation are evaluated and compared with theoretical estimations and it gives good agreement.

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