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Generation dynamics of blobs and holes in reduced boundary plasma turbulence simulation

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The tokamak boundary turbulence is simulated in the vicinity of the last closed flux surface(LCFS) by employing a reduced 2D model, which couples the drift-wave physics, toroidal curvature-interchange and the sheath-interchange dynamics as well as the zonal flow effects. The focus of this work is on the generation dynamics of the density blobs and holes in the core-edge and the scrape-off-layer(SOL) regions, which depends on the non-adiabaticity of the electron and the sheath loss dissipation. The correlation of edge particle transport with the solitary coherent potential dipole structures is discussed.

1. Introduction

The boundary plasma is composed by a part of the core—adjacent to the last closed flux surface (LCFS) (core-edge) and the scrape-off layer (SOL) in divertored fusion devices like tokamak. It is essentially important in future burning plasmas such as the ITER since it is all the transport ways of plasmas particle, heat, current and momentum to the first wall of the devices. Maximizing the fusion power production in burning-plasma devices requires H-mode plasma conditions, which form a "pedestal" in pressure profile in the core-edge region. A ubiquitous feature of the edge transport is the non-diffusive intermittent behavior, which is characterized by a convective blob-type dynamics. Recently, the density blob/hole structures have been observed extensively in various devices with different geometries [1]. A typical one is the emergence of the blobs/holes companying with a solitary potential dipoles or multi-poles. The simulations based on reduced 2D and 3D fluid modeling have qualitatively reproduced some main features of the blob/hole generation and propagation [2].

In this work, the blob/hole generation dynamics is simulated based on a reduced 2D edge turbulence modeling. The key parameter dependence of the blob/hole selection by the turbulent system is investigated. Furthermore, the correlation of the blob/hole dynamics with the solitary coherent potential structures is discussed.

2. Reduced 2D edge turbulence modeling

Conventionally, a 2D drift wave modeling, namely, the so-called Hasegawa-Wakatani(HW) turbulence, is employed to simulate the edge turbulence, in which the parallel electron dynamics is modeled simply through a parallel correlation length. Here we employed an extended HW model, which combines both the core-edge and the SOL regions with an artificially continuous parameter variation. The nonlinear equations governing the perturbed density and potential are [3]

$$\begin{aligned}\partial_t n + [\Phi, n] = \partial_x n_0 \partial_y \Phi + \overline{\alpha}_{dw}(\Phi - N) \\ - \overline{\alpha}_{sh} n + D\nabla_\perp^2 n + S\end{aligned}, \qquad (1)$$

$$\begin{aligned}\partial_t \nabla_\perp^2 \Phi = -[\Phi, \nabla_\perp^2 \Phi] + \overline{\alpha}_{dw}(\Phi - N)/n \\ + \overline{\alpha}_{sh}\Phi - \kappa\partial_y N + \mu\nabla_\perp^4 \Phi\end{aligned}, \qquad (2)$$

Here $N = \ln n$, the terms with $\overline{\alpha}_{dw} = \alpha_{dw0}\alpha_{dw}(x)$ and $\overline{\alpha}_{sh} = \alpha_{sh0}\alpha_{sh}(x)$ model the electron response in the core-edge and the SOL regions, respectively. The toroidal curvature drive is modeled by the term with $\kappa = 2\rho_s/R$. The profiles $\alpha_{dw}(x)$ and $\alpha_{sh}(x)$ are taken as the same as in [3]. $\alpha_{dw0} = 2\rho_s m_i c_s / L_{//}^2 \nu_{ei0} m_e$, $\alpha_{sh0} = 2\rho_s / L_{//}$ with the ion-electron collision rate ν_{ei0}. The density source term $S = \nu(x)[n_0(x) - n]$ is active only in the core-edge region and $S = 0$ in the SOL. The normalization uses Bohm units as $\omega_{ci} t \to t$, $x/\rho_s \to x$, $e\Phi/T \to \Phi$ and $n/n_{00} \to n$ with ion gyro-frequency ω_{ci}, ion sound Larmor radius ρ_s and a reference density at the core region n_{00}.

This reduced model may involve an unstable drift wave, a curvature-interchange mode, a sheath-interchange mode and possibly a Kelvin-Helmholtz mode if the flow is unstable for it. From an eigen-value stability analysis with given initial global profiles, it is observed that the instability spectrum are quite wide for different radial mode numbers, as shown in Fig.1. In addition, it is noticed that the growth rates tend to be the same level for different radial mode numbers. This may have implication for the formation of coherent blob/hole structures since all components with the same fluctuation levels mainly contribute to the solitary structures.

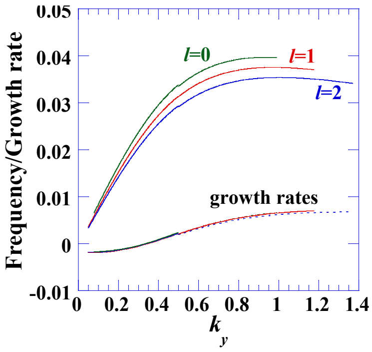

Fig.1 Eigen-frequency (solid) and growth rate (dashed) of linear instabilities for three low order radial mode number l's. $\alpha_{dw0} = 0.01$, $\alpha_{sh0} = 0.001$, $\kappa = 0.002$, $D = \mu = 0.01$.

3. Numerical simulation of blob/hole dynamics

Nonlinear simulations are performed to study the generation of the blobs and holes with different collisionality and parallel correlation length. The former one depends on the plasma temperature and density, possibly also on the impurity and neutral particle effects. The latter one is determined by the q profile at the edge roughly through $L_{//} \sim 1/qR$. It is also different for divertor or limiter plasmas. The simulations are performed for different parameters. Typically, the blobs/holes are simultaneously generated around the LCFS region. The blobs averagely propagate outwards and the holes inwards. Meanwhile, the zonal flows are excited mainly around the LCFS. Note an argument on the role of the zonal flow dynamics in the blob/hole generation mechanism that the blobs/holes may originate from the broken radially-elongated turbulence structures like the so-called streamers by the zonal flows. Two comparative simulations are performed including or artificially excluding the zonal flows with the same simulation setting. It is observed that the zonal flows may enhance the blob/hole generation with strong shearing rate along the LCFS region, but not essential for it. The blobs/holes are still robust without the zonal flow generation.

The preferred structure generation of the blobs or holes are simulated by optimizing the plasma collisionality or the parallel correlation length, which are represented by α_{dw0} and α_{sh0}. It is noticed remarkably that as α_{sh0} decreases, which may be determined by the current (or q) profile, the blob generation is dramatically enhanced and big blobs are formed in the SOL and propagate outwards. Meanwhile, the holes dominate the edge turbulence with decreasing α_{dw0}, as shown in Fig.2. Both the holes inwards and the blobs outwards convert high density plasma from the core-edge to the SOL across the LCFS. The particle transport is characterized by non-diffusive, bursty behavior.

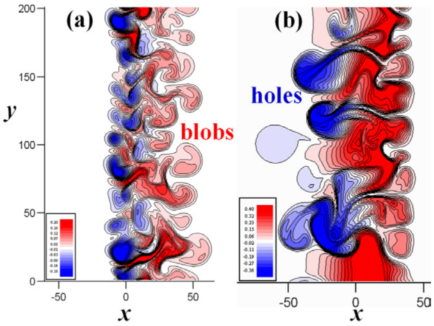

Fig.2 Enhanced density blobs (a) and holes (b) in edge turbulence. The LCFS is located around x=0. The parameters are set as $D = \mu = 0.02$, $\kappa = 2\times10^{-2}$, (a) $\alpha_{dw0} = 10^{-2}$, $\alpha_{sh0} = 10^{-4}$; (b) $\alpha_{dw0} = 10^{-5}$, $\alpha_{sh0} = 10^{-3}$.

Interestingly, it is observed that the density blob/hole structures are companied closely with solitary potential dipoles, even multi-poles. Their propagation directions are along the $\vec{E}\times\vec{B}$ drift. The generation of the blobs and holes may originate from the positive feedback of the convective flow due to the local potential perturbation. As the self-organization of the edge turbulence forms the solitary coherent potential dipole and/or multi-pole structures, the local $\vec{E}\times\vec{B}$ drift is enhanced around the mid-plane of the dipoles so that the density perturbation can grow to form the blobs and holes and propagate following the $\vec{E}\times\vec{B}$ flows. The turbulent particle flux $\Gamma = \langle \tilde{v}_{E\times B}\tilde{n} \rangle$ has been calculated, showing an outward intermittency.

4. Summary

The generation dynamics of the density blobs and holes are simulated in tokamak boundary plasmas. The enhanced blobs or holes have been observed in different parametric regimes. The causal relation of the blob/hole formation with the solitary potential dipole structure has shown the origin of the blob/hole and the intermittent particle transport.

Acknowledgments

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