Eigen mode characteristics of drift wave instability in the presence of magnetic island in tokamak edge plasmas

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Abstract

Multi-scale multi-mode interaction is of key importance in controlling turbulent transport and improving confinement performance [1]. The eigen mode characteristics of drift wave fluctuations interacting with a static magnetic island is studied based on so-called Hasegawa-Wakatani system. Simulations show that a transition of dominant eigen mode from longer to shorter wavelength region occurs at a critical island width, w_c, around which three eigen modes may coexist. Interestingly, when island width greater than the critical value, the global structure is mainly excited in the region between the X- and O-points of the magnetic island. To understand the underlying mechanism of the structural localization, a simulation model with quasi-linear flattening of the equilibrium density profile is proposed. The eigen mode characteristics observed in the simulations can be qualitatively reproduced.

1. Physical model and simulation settings

We use a two-dimensional (2D) standard sheared slab configuration (∂_z=0) as the baseline. The magnetic field can be expressed as B= $B_T\hat{\mathbf{z}}+\hat{\mathbf{z}}\times\nabla\psi$, and B_T is toloidal field. The magnetic flux takes the form$\psi=\hat{s}x^2/2+\tilde{\psi}(x)\cos(k_T y)$, where $\hat{s}$ denotes magnetic shear, k_T is the poloidal wave number of the island, and $\tilde{\psi}(x)$ is the typical profile of the flux perturbation. Because magnetic island evolves in a much slower time scale than micro-turbulence, the assumption of static magnetic island is valid and it be coupled into the gyrofluid equations by the parallel operator$\nabla_{\parallel}$. The full island width is $w=4(\tilde{\psi}(0)/\hat{s})^{1/2}$. [2]

In this work, the linearized HW equations involving the magnetic island effects are written as

$$\frac{\partial\nabla_{\perp}^{2}\phi}{\partial t}=D_{//}\overline{\nabla}_{//}^{2}(n-\varphi)+D_{//}\Lambda(\tilde{\psi},k_T)(n-\varphi)+\mu\nabla_{\perp}^{4}\phi \tag{1}$$

$$\frac{\partial n}{\partial t}+\frac{L_{n0}}{L_n}\frac{\partial\phi}{\partial y}=D_{//}\overline{\nabla}_{//}^{2}(n-\varphi)+D_{//}\Lambda(\tilde{\psi},k_T)(n-\varphi)+\nu\nabla^{2}n \tag{2}$$

Here $D_{\parallel} = T_e L_{n0}\left(n_0 \eta e^2 \omega_{ci} \rho_s\right)^{-1}$, $\bar{\nabla} = \hat{s}x\partial_y$, $L_n = L_{n0}\cosh(2x/\lambda)$, $\lambda = 6.$.

$$\begin{aligned}\Lambda(\tilde{\psi}, k_T) = {} & \hat{s}x\cos(k_T y)(2\partial_x\tilde{\psi}\partial_{yy}^2 + k_T^2\tilde{\psi}\partial_x) + \hat{s}k_T\sin(k_T y)[(\tilde{\psi} - x\partial_x\tilde{\psi})\partial_y + 2x\tilde{\psi}\partial_{xy}^2] \\ & + k_T^2\tilde{\psi}\partial_x\tilde{\psi}\partial_x + \tfrac{1}{2}[k_T^2\tilde{\psi}^2\partial_{xx}^2 + (\partial_x\tilde{\psi})^2\partial_{yy}^2] - \tfrac{1}{2}\cos(2k_T y)[k_T^2\tilde{\psi}^2\partial_{xx}^2 - (\partial_x\tilde{\psi})^2\partial_{yy}^2] \\ & + k_T\sin(2k_T y)\{\tfrac{1}{2}[\tilde{\psi}\partial_{xx}^2\tilde{\psi} - (\partial_x\tilde{\psi})^2]\partial_y + \tilde{\psi}\partial_x\tilde{\psi}\partial_{xy}^2\}\end{aligned} \quad (3)$$

2. Simulation results

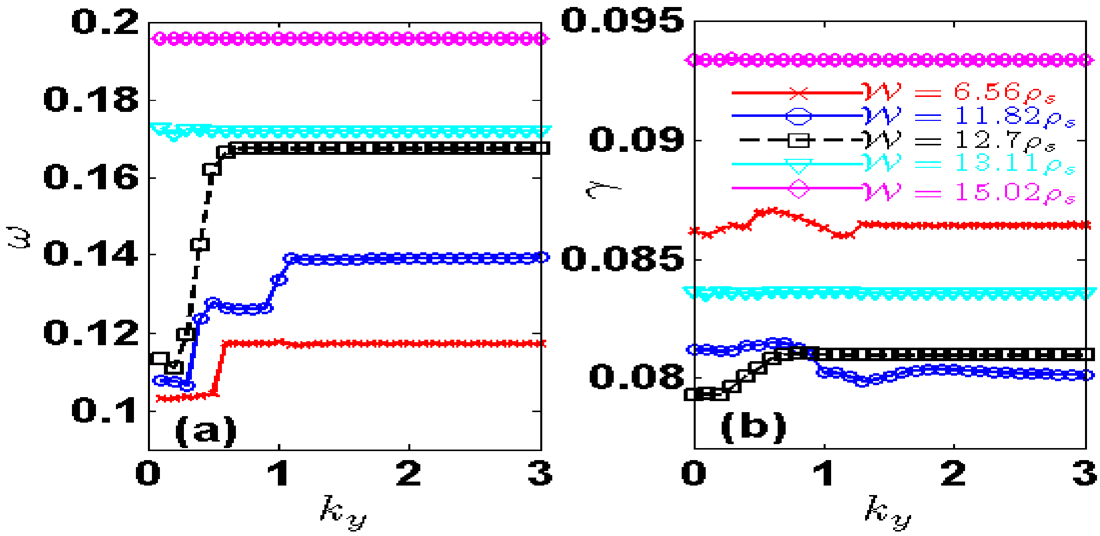

Fig. 1 k_y spectral dependence of both frequency (a) and growth rate (b) for different island widths *w*.

Simulation range L_x=40 with grid number of 512, $L_y=20\pi$ with mode number of 30, and the typical parameters are $D_{\parallel}$=0.05, $\hat{s}$=0.4, μ=ν=0.06, and island widths take 22 values ($1\rho_s$ -$21\rho_s$). Fig. 1 plots k_y spectral distribution of both growth rate and eigen frequency for different island widths. Two spectral staircases of the eigen frequency with approximately same growth rate appear in longer ($k_y \le 0.5$) and short ($k_y > 0.5$) wavelength regions for small island widths, suggesting the coexistence of two eigen mode branches. Meanwhile, one global eigen mode with the same frequency and growth rate evidently dominates whole k_y spectral region for the island width above w_c. Near the critical value w_c, the staircase distribution of the eigen frequency seems to show that three eigen mode branches may coexist with similar growth rate but in different k_y spectral region. Such 3-staircase spectral distribution of the eigen frequency may evidence that the magnetic island can not only couple different k_y components but also different eigen modes.

The explicit dependence of the eigen modes on the island width as illustrated in Fig. 2 shows that small island may stabilize two eigen branches, which dominate at long and short wavelengths, labeled as EM1 and EM2, respectively. However, large island destabilizes another one (EM3), which dominates the short wavelength fluctuations.

Most interestingly, the eigen mode structure (fig. 3(a)) is globally shaped by small islands but it (fig. 3(b)) appears remarkably in the region between the X- and O-points for large islands.

To understand the underlying mechanism of the structural localization, we incorporate the island effect in the resistive drift wave through two steps. First an island-shaped density profile is established by solving the density diffusion in the configuration (n_0=-0.5x+10) with a magnetic island, which is solved based on Eq. (2) without any electrostatic potential fluctuations. Then, the drift wave is simulated with new island-shaped density profile in the configuration by removing the magnetic island.

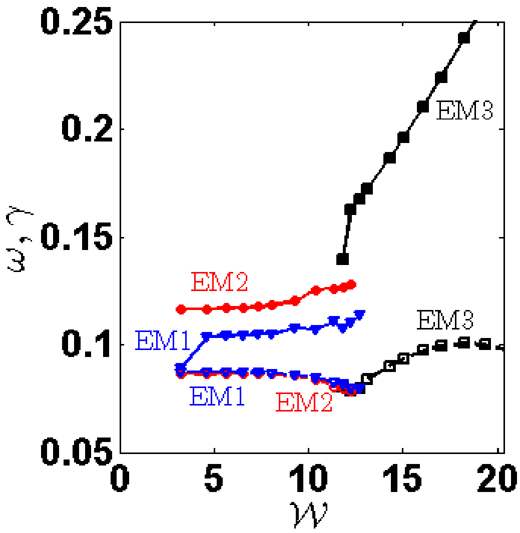

Fig. 2 ky spectral dependence of both frequency fig. 1(a) and growth rate fig. 1(b) for different island widths *w*.

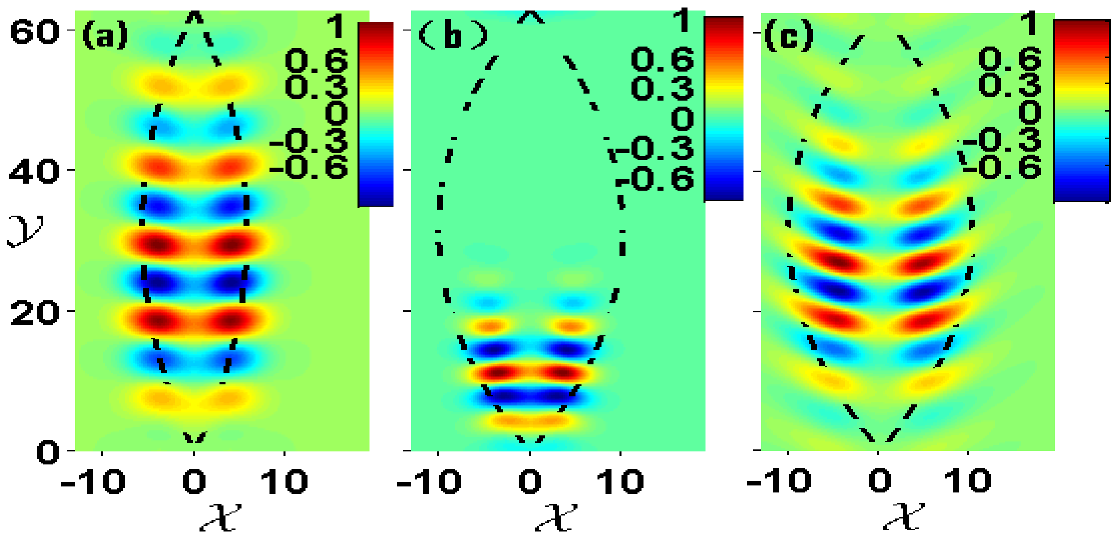

Fig. 3 the 2D eigenfunction for the fluctuation electrostatic potential.

(a) With magnetic island *w*=5.68ρ_s. (b) Withmagnetic island *w*=13.11ρ_s. (c)No magnetic island imbedded but assuming a modeled quasi-linear flattening density profile

Results show that the island-shaped density profile can also cause strong mode coupling of different k_y components. For the island-shaped equilibrium profile induced by large magnetic island, the k_y spectral peak of fluctuation energy is located around k_y≈0.7. Most importantly, the localization of the drift wave eigen mode structure and its position are observed to be similar to those in the simulations with realistic magnetic island effects, as shown in Fig. 3(c). Note that the localized eigen mode structure in this model is still globally extended comparing with Fig. 3(b) for the cases with large island width, which looks to be similar to the case with small magnetic island as shown in Fig. 3(a). Furthermore, comparison with results from the WKB analysis in W&C theory, [3] indicates that the localized position of the global eigen mode structure seems to result mainly from the density profile variation in the y direction between inside and outside magnetic island regions.

3. Conclusions

A small island can stabilize two longer wavelength drift waves with similar growth rate but different frequency. Meanwhile, a large island destabilizes the shorter wavelength drift wave robustly to form a global structure. Such three eigen modes may coexist in the drift wave fluctuations for the island width around w_c. Interestingly, the global structure is mainly excited in the region between the X- and O-points of the magnetic island. The spatial structural localization is mainly from the density profile variation in the y direction between inside and outside magnetic island regions. Furthermore, the magnetic island can couple the micro-scale fluctuations along the poloidal direction to excite the zonal flows even in the linear drift waves. It is observed that the zonal flows due to this linear coupling mechanism tend to be strong as the island width increases, showing a disagreement with experimental observation by a RMP induced magnetic island.[4] The zonal flow dynamics in the drift wave turbulence with magnetic island will be further discussed.

Acknowledgments

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