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Magnetic-island-induced ion temperature gradient mode: Landau damping, equilibrium magnetic shear and pressure flattening effects

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Abstract
Characteristics of the magnetic-island-induced ion temperature gradient (MITG) mode are studied through gyrofluid simulations in the slab geometry, focusing on the effects of Landau damping, equilibrium magnetic shear (EMS), and pressure flattening. It is shown that the magnetic island may enhance the Landau damping of the system by inducing the radial magnetic field. Moreover, the radial eigenmode numbers of most MITG poloidal harmonics are increased by the magnetic island so that the MITG mode is destabilized in the low EMS regime. In addition, the pressure profile flattening effect inside a magnetic island hardly affects the growth of the whole MITG mode, while it has different local effects near the O-point and the X-point regions. In comparison with the non-zero-order perturbations, only the quasi-linear flattening effect due to the zonal pressure is the effective component to impact the growth rate of the mode.

Keywords: magnetic island, magnetic shear, Landau damping, MITG

(Some figures may appear in colour only in the online journal)

1. Introduction
Turbulent transport in a toroidal configuration with nested magnetic flux surfaces is a crucially important issue in magnetic fusion plasmas [1, 2]. Particularly, the ion-scale micro-turbulence which mainly induced by the ion temperature gradient mode can significantly affects the ion transport level and flatten the pressure profile in tokamaks [3–13]. In practice, the nested flux surfaces are intrinsically prone to be broken into chains of magnetic islands by spontaneous tearing modes [14–18] or externally imposed symmetry-breaking perturbations [19–21]. Further growth of long-wavelength magnetic islands as well as their interaction and overlap can lead to very dangerous consequences including the major disruption [22–25]. In recent experimental studies, the interactions between magnetic island and turbulence have also been widely investigated [26–30]. In advanced tokamaks such as ITER, particularly, so-called neo-classical tearing mode [31] is the most dangerous magnetohydrodynamics instability since it is believed to be a very important reason for triggering disruptions. For reducing the size of magnetic islands in experiments, a number of control methods have been developed [32], like electron cyclotron current drive or externally applied static helical field. Consequently, the size of the island is restrained to the relatively stable regime, which is believed to qualitatively contribute to the improvement of the confinement [33, 34].
Evidently, the equilibrium configuration for evolutions of linear and nonlinear ITG modes is no longer the regularly concentric flux surfaces when islands are formed. Since the magnetic topology is changed by islands, plasmas can move quickly in the direction of closed field lines of magnetic islands, leading to the flattening of the plasma temperature (or pressure) inside islands. Moreover, the current profile is also modified with plasma movements and temperature/pressure flattening. Thus, the effect of the island-type magnetic topology itself on the ITG modes should be taken into account. On the other hand, the impact of modification of the temperature gradient that provides the drive for the ITG modes should also be considered, especially near the X-point and O-point regions. Exploring these processes is fundamental to understanding the characteristics of turbulent transport in magnetized plasmas with islands. Therefore, several methodologies have been developed to investigate interactions between magnetic islands and micro-turbulence [35–57].

In an earlier paper [57], we have found that the magnetic islands can generate a broad rational surfaces near the O-point region so that the radially extended global eigenmodes which show a fast growth rate can be excited, and is defined as the magnetic-island-induced ITG (MITG) mode. In addition, the magnetic curvature effect of island fields may induce both radial mode coupling and poloidal mode coupling, which is believed to play a stabilizing role [57, 58].

In this paper, we further study the MITG mode, considering the effects of Landau damping, equilibrium magnetic shear (EMS), and pressure flattening. We found that the appearance of magnetic islands enhances the Landau damping of the system and hence reduces the growth rate of the MITG modes. Moreover, decreasing the EMS has a destabilizing effect on the unstable modes. In addition, the different roles of the quasilinear flattening effect due to zonal pressure and the pressure flattening effect inside the magnetic island are elucidated.

The remainder of this paper is organized as follows: in section 2, the model equations used in the numerical simulations are introduced. In section 3, we first presented the numerical results and then discussed the underlying physical mechanisms in the three subsections. Finally, the obtained results are summarized in section 4.

2. Model equations

For simplicity, we consider the two-dimensional (2D) slab configuration ($\delta_0 = 0$), and the magnetic field is then given as

$$B = B_T \hat{e}_z + \hat{e}_x \times \nabla \psi,$$  

(1)

with $B_T$ the toroidal field. $\hat{e}_x$, $\hat{e}_y$, and $\hat{e}_z$ are the unit vectors corresponding to the radial, poloidal, and toroidal directions in tokamak plasmas, respectively. In sheared magnetic fields, the magnetic flux of islands may be expressed as

$$\psi = \hat{s} x^2 / 2 + \tilde{\psi}(x) \cos(k_T y),$$  

(2)

where $\hat{s}$ denotes the EMS in the absence of islands, $k_T$ represents the poloidal wave number of the magnetic island, and $\tilde{\psi}(x)$ denotes the typical profile of the flux perturbation of a single island given by [14]:

$$\tilde{\psi}(x) = \psi(0) \exp(i k_T x).$$  

(3)

Thus in the ‘constant-\(\psi\)’ regime, the full island width is given as [59]

$$w = 4 \sqrt{\psi(0) / \hat{s}}.$$  

(4)

It is a valid assumption for the magnetic island to be time-independent since it evolves with a much slower time scale than that of the micro-turbulence like the ITG mode, e.g. in the Rutherford phase or saturation phase [59]. Effects of magnetic islands can be incorporated into the gyrofluid equations through the parallel gradient operator $\nabla_{||}$ is given as a general expression,

$$\nabla_{||} f = \hat{e}_x \times \nabla \psi \cdot \nabla_{||} f = \nabla_{||} f + [\psi \cos(k_T y) , f],$$  

(5)

here $\nabla_{||} = \partial_i \hat{e}_i + \partial_\psi \hat{e}_\psi$, and Poisson bracket $[g, f] = \partial_i g \partial_i f - \partial_i f \partial_i g$.

It is noticed through equation (5) that the parallel gradient operator $\nabla_{||}$ includes radial dependence. When the Poisson bracket in equation (5) is unfolded based on the wave number matching condition, the normalized electrostatic ITG equations consisting of electric potential $\phi$, parallel flow $v_{||}$, and ion pressure $p$ can be written as follows [60],

$$\partial_t V^k = (1 + K \nabla^2_\psi) \partial_t \phi^k + \nabla[v^k_{||} + \Lambda(v^k)]$$

$$- [\phi, \nabla^2 \phi^k] + \partial_t \phi^k \partial_t \phi + \mu_{||} \nabla^2_\psi \phi^k,$$  

(6)

$$\partial_t v^k_{||} = -\nabla_\psi (\phi^k + p^k) - \Lambda(\phi^k + p^k)$$

$$- [\phi, v^k_{||}] + \eta_{\perp} \nabla^2_\psi v^k_{||},$$  

(7)

$$\partial_t p^k = -K \partial_t \phi^k - \Gamma (\nabla v^k_{||} + \Lambda(v^k)) - (\Gamma - 1)$$

$$\times \left[ \frac{\hat{s}}{2} |v^k_{||}| (p^k - \phi^k) - [\phi, p^k] + \chi_{\perp} \nabla^2 \phi^k, $$  

(8)

where $V^k \equiv (\nabla^2_\psi + \delta_0^2 - 1) \phi^k$, and $\Gamma = \frac{q_i}{q_i q_f} \hat{s} = L_A / L_A$ and $K = 1 + \eta_{||}$ with $\eta_{||} = L_{\perp} / L_{\perp}$, where $L_{\perp}$ represents the scale lengths of plasma density, ion temperature, and magnetic field, respectively. The temperature ratio is assumed as $T_e / T_i = 1$. The terms with $\delta_\perp$ and $\partial_\perp$ in equation (6) originate from the corrected adiabatic electron response to zonal flows [4], and then $\delta_\perp = 0$ is for zonal flows and $\delta_\perp = 0$ is for ITG fluctuations. $\mu_{||}$, $\eta_{\perp}$ are the numerical cross-field viscosities, and $\chi_{\perp}$ is the thermal conductivity, which absorb energy in high-wavenumber regimes. The kinetic Landau damping physics can be studied by the Hammett–Perkins closure model [60] with the parallel heat flux $q_{||} \sim i k_T T_i \sqrt{8 / \pi / |k_T|}$. The common operator that originates from the Poisson bracket in equation (5) is defined as

$$\Lambda(f^k) \equiv \frac{1}{2} \partial_t \tilde{\psi} (i k_T f^{k+} + f^{k-}) + \frac{i}{2} (i k_T \tilde{\psi} (\delta_t f^{k+} - \delta_t f^{k-}),$$  

(9)

where $k_{\perp} = k_x \pm k_y$. $\Lambda(f^k)$ denotes the expression of radial and poloidal mode couplings induced by islands. The perturbed quantities are conventionally normalized as [60],
(x, y, z, t) \rightarrow (x/\rho_i, y/\rho_i, z/L_n, v_{ni}t/L_n),
(\phi, v_\phi, p) \rightarrow (L_n/\rho_i)(e\bar{\phi}/T_{\|}, \bar{\phi}/v_{ni}, \bar{\rho}/p_{i0}),

with \rho_i = v_{ni}/\omega_{ci}, v_{ni} = \sqrt{T_{ni}/m_i}, and \omega_{ci} = eB/m_i c.

To examine the characteristics of the ITG mode in the presence of magnetic islands, we simulate the linear evolution of the ITG system by solving numerically the linearized equations (5)–(7) with a 2D initial value code [60]. A finite difference method is applied in x direction with fixed boundary condition and a Fourier decomposition is used in y direction. The simulation domain is \( r = 100 \rho_i \) and \( pr = 20\pi \rho_i \), and the typical parameters are \( k_T = 0.1, \eta_l = 4.2, \) and \( \mu_L = \eta_l = \chi_L = 0.8. \)

3. Numerical results

It has been identified that [57], as illustrated in figure 1, the newly produced rational surfaces (i.e., \( k_l = k \cdot \hat{B}/B_0 = 0 \) surfaces) by wide islands are very dense when contributions of all \( k_x-k_y \) pairs are superposed. As a result, the ITG perturbations on these magnetic surfaces can be strongly coupled with each other, forming a radially-widened global eigenmode with a larger growth rate, namely the MITG mode [57].

Figure 2 shows the eigenmode potential contours in the absence and presence of an island. It is found that the mode coupling between radial and poloidal magnetic-island-induced mode plays a stabilizing role by enhancing the energy transfer to the high-wavenumber, strongly-damped fluctuation regimes [57, 58], where the instability can be efficiently suppressed due to the finite Larmor radius effect or the viscosity damping.

In sections 3.1 and 3.2, we discuss the effects of Landau damping and EMS on the MITG modes, respectively, with neglecting the pressure flattening. In section 3.3, the roles of the pressure flattening are addressed in detail.

3.1. Effect of Landau damping

In the gyrofluid (or called Landau fluid) model adopted, the kinetic Landau damping effect is involved in the term \( |k| \) in equation (8) [61]. To account for Landau damping accurately, we should calculate the vector \( \bar{k}_l \) in the field lines’ direction of the total magnetic field including the equilibrium component and the perturbed component of islands. Figure 3 shows the growth rates of the MITG modes in the two cases, i.e., calculating \( \bar{k}_l \) along the equilibrium field and along the total field. It is seen that the island-enhanced Landau damping reduces the growth rate \( \gamma \) and that the reduction becomes even clearer with increasing island width \( w \). It is physically reasonable that the islands introduce the radial magnetic field and hence enhance the Landau damping through increasing \( \bar{k}_l \).

In the following discussions, we calculate \( \bar{k}_l \) along the total field.

3.2. Effect of EMS

Effects of EMS on the ITG mode in the absence of islands have been intensively studied (for example, see [62]). It should be mentioned that in the parameter regimes used in this work, decreasing EMS \( \hat{s} \) destabilizes the conventional ITG mode. Here we focus only on the effects of EMS associated with islands.

Figure 4 shows the dependence of growth rate \( \gamma \) on island width \( w \) in different EMS cases. In the small island region (roughly \( w < 15\rho_i \)), the stabilizing effect due to the mode
coupling in the $\hat{s}=0.1$ case is much weaker than that in the $\hat{s}=0.4$ case. Equation (4), $\sqrt{\hat{\psi}(0)/\hat{s}} \sim w$, indicates that for a fixed $w$, the amplitude of $\hat{\psi}(0)$ in the $\hat{s}=0.1$ case is reduced to one-fourth of its original value in the $\hat{s}=0.4$ case. Notice that as expressed in equation (9), $\hat{\psi}$ in $\Lambda(f^k)$ just stands for the strength of the mode couplings induced by islands. Accordingly, it is seen that the mode coupling is weaker in the smaller $\hat{s}$ regime and then plays a more weakly stabilizing role.

Another prominent difference is that in the large island region ($w > 19\rho_i$), the MITG mode becomes more unstable with increasing $w$ in the $\hat{s}=0.1$ case than in the $\hat{s}=0.4$ case. Two reasons associated with islands are identified. Firstly, although the positions of non-zero solutions of the rational surfaces for a pair of $k_x$ and $k_y$ is dependent on $\hat{s}$ [57], the destabilizing mechanism which is induced by the newly-produced dense distribution of rational surface is not very sensitive to the EMS. However, as discussed above, the strength of the mode couplings by islands is more sensitive to the EMS. Thus in the large $w$ regime with $\hat{s}=0.1$, the net destabilizing effect is more prominent. Secondly, as shown in figure 2(b), the potential contour of the MITG modes is radially widened near the O-point region. Actually, the widened structure is superposed by all the $k_y$ harmonics, which requires that the perturbations of at least some $k_y$ harmonics are radially widened. Figures 5 and 6 plot the potential contours of the first eight $k_y$ harmonics, respectively, in the absence and presence of islands. Compared with those in figure 5, the eigenmode structures of most $k_y$ harmonics in figure 6 are extended radially. Furthermore, it is noted in figure 6 that their $l$ numbers are clearly increased by islands, where $l$ is the radial eigenmode number of Weber equation. It

![Figure 2](image1.png)  
**Figure 2.** Contour plots of linear potential perturbations in the absence (a) and presence (b) of the magnetic island at a same time with $w = 19\rho_i$ when $\hat{s} = 0.4$. The thick stream-lines with arrows represent the magnetic field lines.

![Figure 3](image2.png)  
**Figure 3.** Dependence of the linear growth rate $\gamma$ on island width $w$, with calculating $\hat{k}_y$ along the equilibrium field and along the total field. Here $\hat{s} = 0.4$.

![Figure 4](image3.png)  
**Figure 4.** Dependence of the linear growth rate $\gamma$ on island width $w$ with magnetic shear $\hat{s} = 0.1$ and $\hat{s} = 0.4$. 

has been demonstrated theoretically [62] and numerically [63] that the increase of the \( l \) numbers has a destabilizing effect on the ITG mode in the low EMS regime. Similarly, this is also an important destabilizing mechanism for the MITG modes in the large \( w \) region in the \( \delta = 0.1 \) case. Essentially, all the \( k_y \) harmonics with increased \( l \) numbers contribute to this mechanism since their growth rates are the same [58], unlike the case without islands, in which the most unstable harmonic is dominant.

### 3.3. Effect of pressure flattening

In the presence of an island, the pressure profile within the island separatrix will be flattened since the plasma movement is faster along the field lines than across the field lines. To study the effect of the pressure flattening, let us first identify the pressure profiles in the self-consistent, nonlinear simulation by solving the 2D nonlinear equations (5)–(7). In the saturation phase of the MITG turbulence, a turbulent pressure contour consisting of all perturbed \( p^{k_y} \) harmonics (excluding the initial pressure gradient profile, \( P_{\text{eq}} \), associated with \( \eta \)) in the quasi-steady state is plotted in figure 7. By means of Fourier analysis, it is found that the pressure contour is mainly composed of \( \tilde{P}_0 \) (i.e., \( p^{k_y=0} \)) and \( \tilde{P}_1 \) (i.e., \( p^{k_y=0.1} \)) and that other higher-order \( p^{k_y} \) components only modify the pressure contour slightly. Here \( \tilde{P}_0 \) is called as the zonal pressure, which causes the quasi-linear flattening effect of the pressure and \( \tilde{P}_1 \) mainly contributes to the formation of the pressure island corresponding to the magnetic island under the magnetic field frozen-in law. Figure 8 gives the typical profiles of the combined pressure by \( P_{\text{eq}}, \tilde{P}_0, \) and \( \tilde{P}_1 \) across the X-point and the O-point. Such pressure profiles are in agreement with those obtained by numerically solving an energy transport equation [64]. Obviously, the pressure
gradient across the X-point is greater than that across the O-point. This difference originates from the different phases of $\tilde{P}_1$. As compared in figure 9, the phase of $\tilde{P}_1$ is the same as $\tilde{P}_0$ across the O-point, counteracting $P_{\text{eq}}$ together with $\tilde{P}_0$, whereas across the X-point it is opposite to $\tilde{P}_0$, enhancing $P_{\text{eq}}$.

To examine the different roles of $\tilde{P}_0$ and $\tilde{P}_1$ in driving the MITG mode in the case of island width $w = 19 \rho_i$, we artificially impose $\alpha \tilde{P}_0$ and $\beta \tilde{P}_1$ in the linear system besides the equilibrium pressure $P_{\text{eq}}$, where $\alpha$ and $\beta$ are only the coefficients of $\tilde{P}_0$ and $\tilde{P}_1$ for regulating their amplitudes, respectively. The effect of $\tilde{P}_0$ on the growth rate $\gamma$ is revealed in figure 10. As expected, increasing $\tilde{P}_0$ stabilizes the MITG mode by reducing the actual drive. Figure 11 reveals the effects of $\tilde{P}_1$ on $\gamma$ near X-point and O-point regions as well as in the whole MITG system. It is found that due to the different phases, $\tilde{P}_1$ works to enhance (or weaken) the MITG mode instability locally near the X-point (or O-point) by increasing (or decreasing) the local pressure gradient. It is interesting to point out that the presence of $\tilde{P}_1$ almost does not have an influence on the MITG mode growth rate in whole system because the $\tilde{P}_1$-induced opposite effects are just counteracted by themselves. It is therefore indicated that only $\tilde{P}_0$ has an obvious effect on the whole MITG mode, although the formation of the pressure island structure are owing mainly to $\tilde{P}_0$ and $\tilde{P}_1$. Additionally, it is found that the perturbations of the MITG mode are still widened near the O-point region although $\tilde{P}_0$ and $\tilde{P}_1$ participate in the initial equilibrium. This may be due to that the characteristics of the eigenmode structure as shown in figure 2(b) is mainly determined by the rational surfaces distribution in the linear phase.

Finally we note that the static $\tilde{P}_1$ is imbedded into the linear system as a component of equilibrium pressure by means of the approach in [58] where a vortex flow was considered. Due to its curvature effect, the $\tilde{P}_1$ can also induce

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**Figure 6.** The structure contours of the $k_y$ harmonics in the presence of islands. Here $\delta = 0.4$. 

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the 2D mode couplings via the convective term $[\phi, p]$. However, we have numerically verified that the $\tilde{P}_j$-induced mode couplings are much weaker than those induced by vortex flows or magnetic islands so that the resultant stabilizing effect can be neglected.

Although the initial equilibrium condition for linearly driving the MITG mode is hardly satisfied in realistic tokamak discharges, the nonlinear excitation of the mode can occur through plasma heating or due to the collapse of the quasi-linear flattening temperature/pressure. It has been observed numerically in self-consistent 5-field nonlinear gyrofluid simulations $^{[55, 65]}$ that the MITG mode is nonlinearly triggered by the collapse of the temperature island inside the magnetic separatrix when the magnetic island width exceeds a threshold value in a quasi-steady state $^{[41]}$. In such a nonlinear excitation, all harmonics again grow exponentially with a larger growth rate than the original linear ones, reflecting the linear MITG mode with similar features as reported in $^{[57]}$ and this paper. In addition, in a self-consistent

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**Figure 7.** Typical contour of the perturbed pressure (excluding the initial equilibrium pressure) in the presence of the island $w=19\rho_i$. The data are obtained from the quasi-steady state in the self-consistent and nonlinear simulation.

**Figure 8.** Pressure profiles consisting of $P_{\text{eq}}$, $\tilde{P}_0$ and $\tilde{P}_1$ across the X-point and the O-point. $\tilde{P}_0$ and $\tilde{P}_1$ are obtained from the quasi-steady state in the self-consistent nonlinear simulation. $P_{\text{eq}}$ is related to the pressure at O-point or X-point of the island is drawn roughly based on $\eta_i$.

**Figure 9.** Profiles of $P_{\text{eq}}$, $\tilde{P}_0$ and $\tilde{P}_1$ across the (a) X-point and (b) the O-point. $\tilde{P}_0$ and $\tilde{P}_1$ are obtained from the quasi-steady state in the self-consistent nonlinear simulation. $P_{\text{eq}}$ is related to the pressure at O-point or X-point of the island is drawn roughly based on $\eta_i$.

**Figure 10.** Dependence of the linear growth rate $\gamma$ on $\alpha$ in the case of the island width $w=19\rho_i$. Here $\lambda = 0.4$. 

Consequently, the island width in the whole system. Here $\delta = 0.4$.

3-field nonlinear gyrofluid simulation, the pressure structure with respect to the magnetic island is found to change to an entirely new profile, as a bifurcation, due to the nonlocal interaction between islands and micro-turbulence, in which the kinetic energy grows to a much higher level [54]. Such a phenomenon is believed to result from the magnetic topology change according to several recent experimental studies [27–30]. On the other hand, it has been also observed in several fusion devices that the temperature island structures may be broken by nonlinear self-organized activities, while the magnetic islands still keep well [66–68]. These evidences can provide the conditions of plasma profiles for exciting the MITG mode nonlinearly. However, in order to make a better understanding of the transport processes inside the magnetic island, a more accurate 3D global simulation is needed for a further study.

4. Summary

In the present work, we investigated the effects of the Landau damping, the EMS, and the pressure flattening on the MITG mode, using the gyrofluid model in slab geometry. Numerical results show that the Landau damping is enhanced by the radial magnetic fields of the islands and then plays a role in stabilizing the mode. Moreover, the eigenmode structure is widened near the O-point region due to the newly-formed rational surfaces distribution, which requires that the eigenfunctions of most $k_{\perp}$ harmonics are radially extended. Consequently, the $l$ numbers of the extended $k_{\perp}$ harmonics are increased, which act as a destabilizing role in the low EMS regime. For a fixed island width, on the other hand, the strength of radial and poloidal couplings induced by islands is found to be proportional to the EMS, and hence the associated stabilizing effect is reduced with decreasing the EMS. In addition, it is shown that the pressure islands are due mainly to the quasi-linear flattening pressure and the long-wavelength perturbed pressure. It is identified that the quasi-linear flattening pressure affects the linear growth of the MITG mode significantly. While the pressure flattening inside the island play a stabilizing (or destabilizing) influence on the local growth of the MITG mode by decreasing (or increasing) the pressure gradient around the O-point (or X-point), it has a neglectable effect on the growth rate of the whole MITG mode because the local effects caused locally around the O-point and the X-point are just counteracted. Finally, the conditions of the MITG mode nonlinear excitation, which contains the characteristics of the linear mode, are discussed. Detailed discussions of the nonlinear excitation will be reported in a separate publication soon [69]. Since this work is done using a local slab model which cannot precisely discuss the complicated processes inside the magnetic island, an advanced simulation code with global effect in 3D geometry is of great significance in studying transport processes in the future.

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