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Simulation on the transition of electrostatic instabilities in EAST steady-state scenario

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Abstract

The parameter dependence of transition between electrostatic instabilities is studied using gyrokinetic simulation based on a real discharge of steady-state scenario in the Experimental Advanced Superconducting Tokamak. The scan of radial locations shows that trapped electron mode (TEM) dominates around the core while the ion temperature gradient mode (ITG) simultaneously dominates outside. The maximum growth rate of TEM appears around $\rho = 0.24$, where the maximum electron temperature gradient R/L_{Te} locates, ρ is the normalized poloidal flux. Effects of the parameters on the transition between TEM and ITG instability are studied at $\rho = 0.24$. It is found that TEM dominates in the scanning with individually changing R/L_{Te} from 2.50 to 25.02 or the density gradient R/L_n from 1.38 to 13.76. Meanwhile, the electron-ion temperature ratio T_e/T_i is found to destabilize TEM, the effect of T_e is more sensitive than that of T_i . The dominant instability diagrams in the $(R/L_{Te}, R/L_{Ti})$ plane at different T_e/T_i and R/L_n are numerically obtained, which clearly show the parameter range of the dominant TEM or dominant ITG instability region. It is found that the dominant TEM region becomes narrower in the plane by decreasing R/L_n when $T_e/T_i > 0.5$.

Keywords: gyrokinetic simulation, EAST, TEM, ITG

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

1. Introduction

The ion temperature gradient (ITG) and trapped electron mode (TEM) are two typical electrostatic instabilities in tokamak devices. They are considered as candidates for causing anomalous transport [1, 2], which seriously impacts the confinement performance of fusion devices. The characteristics of TEM and ITG instability have been widely studied in experiments [3], simulations [4, 5], and theories [6], and results have shown that the two instabilities can coexist [7–9] and transition [7, 10–12] under specified

conditions. The regulating transition mechanisms between dominant instabilities and their dependencies on plasma parameters are essential to understanding the global nature of anomalous transport.

The destabilization of electrostatic instabilities can be affected by the factors such as magnetic shear [13–15], trapped electrons [16], impurities [8, 17], fast ions [18–22], collision [23] and zonal flow [24]. Besides, the electrostatic instabilities are generally affected by the plasma temperature and density gradients. The gyrokinetic simulations with GKW [25, 26] in JET showed that the transition from ITG to TEM was located in the area where the growth rate increases dramatically with the electron temperature gradient R/L_{Te} [5].

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Simulations with GS2 [27] in ASDEX-U showed that the electron and ion heat fluxes driven by TEM increased with increasing R/L_{Te} , but the fluxes driven by ITG barely changed [28]. Studies on the Experimental Advanced Superconducting Tokamak (EAST) with the gyrokinetic toroidal code (GTC) [29] revealed the destabilizing effect of R/L_{Te} on TEM and showed that R/L_{Ti} slightly reduces TEM turbulence [30]. The transition from TEM to ITG was observed in DIII-D with TGLF [31, 32] when R/L_{Ti} increased [33]. Simulation with CGYRO [34] also showed that R/L_{Ti} impacted the ITG instability [4]. In addition, the transition could also occur when the density gradient R/L_n is changed, and there is a temperature gradient threshold for an inverted density profile where both TEM and ITG are stable below the threshold [35]. The threshold effect is ubiquitous and is still to be understood since it relates to many parameters [36]. It is believed that the temperature ratio T_e/T_i is one of the important factors affecting the threshold [37].

EAST is the first fully superconducting tokamak with an ITER-like configuration, plasma control, and heating schemes. Two main types of advanced scenarios, i.e. the hybrid and steady-state scenario, are developed, and a high fusion triple product has been obtained [38]. The high poloidal beta β_p H-mode plasma scenario is an attractive candidate for steady-state operations and has been extensively studied on EAST. Here, β_p is defined as the ratio of the plasma pressure to the poloidal magnetic field pressure, namely, $\beta_p = P/(B_p^2/2\mu_0)$, where P is the plasma pressure, B_p is the poloidal magnetic field, and μ_0 is vacuum permeability. Electron heating is dominant with the equipped heating and current drive systems in EAST, and the transport is mainly induced by TEM in EAST [39]. If the electron temperature is close to the ion temperature with high ion heating power, ITG instability may dominate when R/L_{Ti} is larger than R/L_{Te} [30]. Further research on the parameter dependence between dominant TEM and ITG instability is necessary to understand the transition of electrostatic instability in the EAST steady-state scenario.

The paper is organized as follows. In section 2, the experiment and simulation conditions are introduced. In section 3, the properties of dominant instability, including the properties of ITG and TEM at different radial locations, the effects of R/L_{Te} , R/L_{Ti} , R/L_n , and T_i/T_e , are investigated by gyrokinetic simulation. Section 4 describes the dominant instability diagrams with different R/L_n and T_i/T_e . The conclusions and discussions are presented in section 5.

2. Experiment and simulation conditions

EAST has successfully demonstrated a compatible core and edge integration in high β_p scenario via feedback control of the total radiation power [40]. A typical discharge (shot 94437) is chosen in this work. The main parameters of shot 94437 are shown in figure 1. The major radius of EAST is $R_0 = 1.90$ m, and the minor radius is $a = 0.45$ m. The plasma current I_p is 400 kA, and the toroidal magnetic field $B_T = 2.4$ T; the loop voltage V_{loop} is near zero; the power

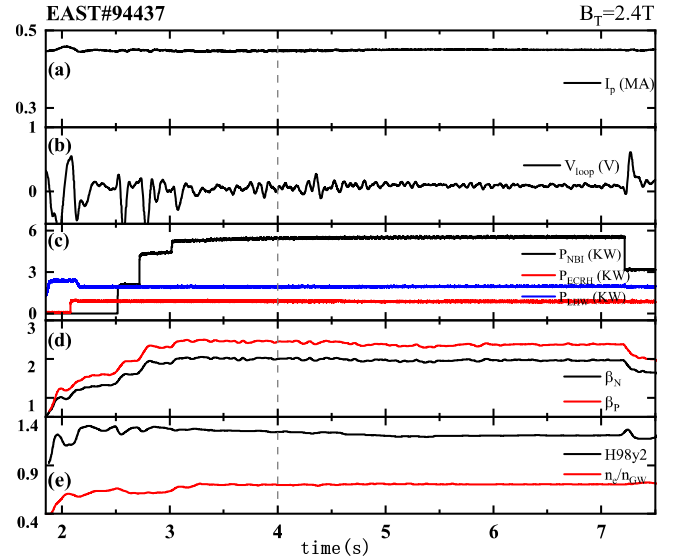


Figure 1. Time evolution of the typical discharge #94437 on EAST: (a) plasma current, (b) loop voltage, (c) auxiliary heating powers of LHW, ECRH, and NBI, (d) normalized beta β_N and poloidal beta β_p , (e) energy confinement factor H_{98y2} , and the electron density normalized to Greenwald density n_e/n_{GW} .

injection includes neutral beam injection (NBI ~ 5.4 MW), electron cyclotron resonance heating (ECRH ~ 2.0 MW), and lower hybrid wave (LHW ~ 1.0 MW); both normalized beta β_N , where $\beta_N = 2\mu_0 Pa/(I_p B_T)$, and poloidal beta β_p are significantly raised with the injection of NBI, and remain stable at relatively high values ($\beta_N \sim 2.5$ and $\beta_p \sim 2.0$); the electron density normalized to Greenwald density n_e/n_{GW} is about 0.7, and H_{98y2} is up to 1.2. A time slice with stable plasma parameters at 4.0 s is chosen for further study below, as shown in the dashed line in figure 1.

The gyrokinetic simulations use experimental plasma profiles at 4.0 s and real magnetic equilibrium obtained by equilibrium fitting code [41]. Electron density n_e , electron temperature T_e , ion temperature T_i , safety factor q , and magnetic shear s profiles are shown in figure 2(a), where ρ is the normalized poloidal flux and ion density n_i is equal to n_e . These profiles are obtained from a fitting of experimental data. Figure 2(b) shows the corresponding gradient R/L_{Te} , R/L_{Ti} , and R/L_n . The electron temperature on-axis T_{e0} ($=5.30$ keV) is much larger than the ion temperature on-axis T_{i0} ($=1.47$ keV), and R/L_{Te} reaches its maximum of 25.02 at $\rho = 0.24$, which is much larger than R/L_{Ti} . The ion and electron temperature profiles are comparable when $\rho > 0.57$.

The electrostatic instabilities are studied using the radially global initial-value code GTC [29, 42]. The magnetic flux coordinates, namely the Boozer coordinates (ψ , θ , ζ), have been used for describing the equilibrium magnetic field of toroidal confinement systems in GTC, where ψ is the poloidal flux, θ is the poloidal angle, and ζ is the toroidal angle. A field-aligned mesh can be conveniently defined with the Boozer coordinates. The gyrokinetic particle simulation uses the Particle-in-Cell method to solve the gyrokinetic equation, which is essentially a Monte-Carlo approach to solve the reduced dynamic equation in the 5D phase space of

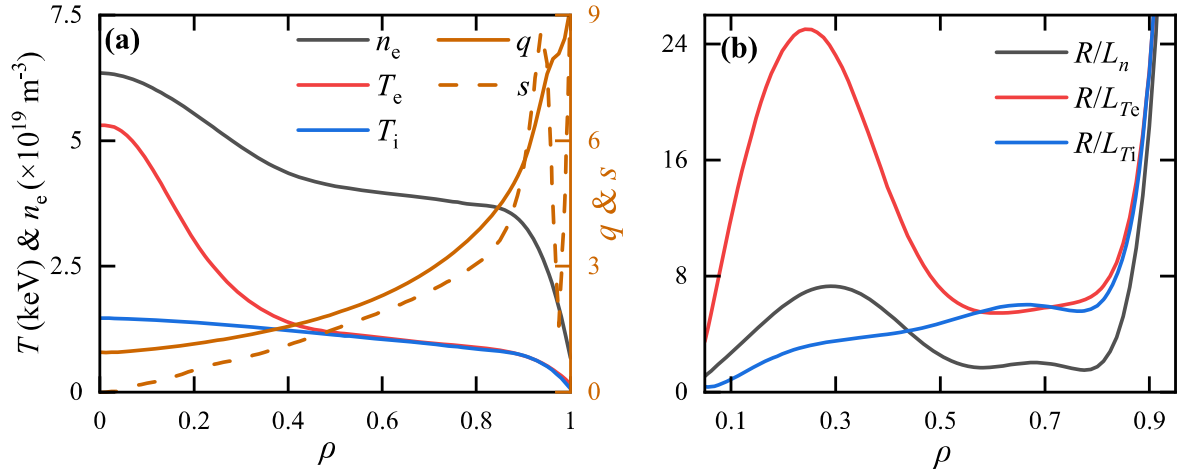


Figure 2. Experimental profiles at 4.0 s of shot 94437, including (a) electron density n_e , electron temperature T_e , ion temperature T_i , safety factor q , and magnetic shear s ; (b) the gradients of experimental profiles.

($\psi, \theta, \zeta, v_{||}, \mu$) [43], where $v_{||}$ is the parallel velocity for the particle and μ is the magnetic moment. The four-point average method, the δf approach, the split-weight scheme, and other schemes are included to improve simulation features [44]. Gyrokinetic methods describe the ions while a fluid-kinetic hybrid electron model is used to improve the computational efficiency of the simulation [45]. The main idea of this hybrid model is to divide the electronic response into the adiabatic part of the lower order and the non-adiabatic part of the higher order.

In our simulation, the ion effective charge Z_{eff} is 2.2 because of impurities. Kinetic electrons are considered, but the fast ion effects and collision effects are neglected. After performing a series of convergence analyses, the time step size is set as $t_{\text{step}} = 0.03R_0/c_s$, where $c_s = \sqrt{T_{e0}/m_i}$ is the ion sound speed, and m_i is the mass of ions. Note that all the growth rate γ and real frequency ω are normalized to c_s/R_0 . Several simulations on the dominant instability at $r = 0.50a$ are carried out. The simulation radial intervals, which are centered at $0.50a$, are changed from $0.10a$ to $0.80a$, in another word, the simulation radial domains are changed from $(0.45a, 0.55a)$ to $(0.10a, 0.90a)$. It is found that the variations of growth rate and real frequency for dominant instability among different simulation radial intervals are within 10%. On this basis, the simulation radial interval is set as $0.20a$ to save computational resources.

3. Properties of dominant instability

3.1. Properties of ITG and TEM instability at different radial locations

Linear, electrostatic simulations have been carried out to diagnose instabilities at the different radial locations from $\rho = 0.10$ to 0.75 , namely from $r = 0.20a$ to $0.76a$. The radial and poloidal grid points at different radial locations are adjusted so that the grid length is comparable to the ion Larmor radius $\rho_s = m_i c_s / eB$.

The real frequency and growth rate of dominant instability versus $k_\theta \rho_s$ at different radial locations with experiment profiles are given in figures 3(a) and (b), respectively. $k_\theta = nq/r$, where n is the toroidal mode number. Alternatively, by interpolating the discrete data shown in figures 3(a) and (b), the 2D contours of real frequency and growth rate in the $(k_\theta \rho_s, \rho)$ plane are obtained and presented in figures 3(c) and (d), respectively. The dominant instability type is distinguished by the sign of the real frequency. If $\omega > 0$, the instability rotates in the electron diamagnetic drift direction, TEM dominates; on the contrary, $\omega < 0$ indicates that instability rotates in the ion diamagnetic drift direction, ITG instability dominates. The dominant TEM and ITG instabilities are presented in red and blue in figure 3(c), respectively. The dashed pink line with $\omega = 0$ in figure 3(c) represents the boundary between the dominant TEM and ITG instability region, which is located around $\rho = 0.66$, that is, the TEM dominates when $\rho < 0.66$, and the ITG instability dominates when $\rho > 0.66$.

As shown in figure 3(b), the growth rate of dominant TEM mainly increases with $k_\theta \rho_s$ for each diagnosed radial location, except for a significant reduction in $k_\theta \rho_s > 0.6$ at $\rho = 0.49$. When TEM dominates, for a fixed $k_\theta \rho_s$, the growth rate increases firstly and then decreases by enlarging the diagnosed radial location, the maximum growth rate appears around $\rho = 0.24$. Analogously, the dependence of R/L_{Te} on the diagnosed location in figure 2(b) shows a similar tendency. It is indicated that the TEM is more unstable with higher R/L_{Te} [3, 5, 46]. The growth rates of ITG instability at $\rho = 0.70$ and 0.75 are close to the growth rate of TEM at $\rho = 0.62$, which are much smaller than those at other radial locations. From figure 3(d), a region with $\gamma = 0$ can be found with larger $k_\theta \rho_s$ and ρ , which represents that ITG instabilities with shorter wavelengths are not easy to excite. We mention that the properties of instability at different radial locations are closely related to the internal transport barrier, as discussed in reference [46].

The poloidal cross-sections of potential fluctuation for typical dominant TEM and ITG instability at $30R_0/c_s$ are

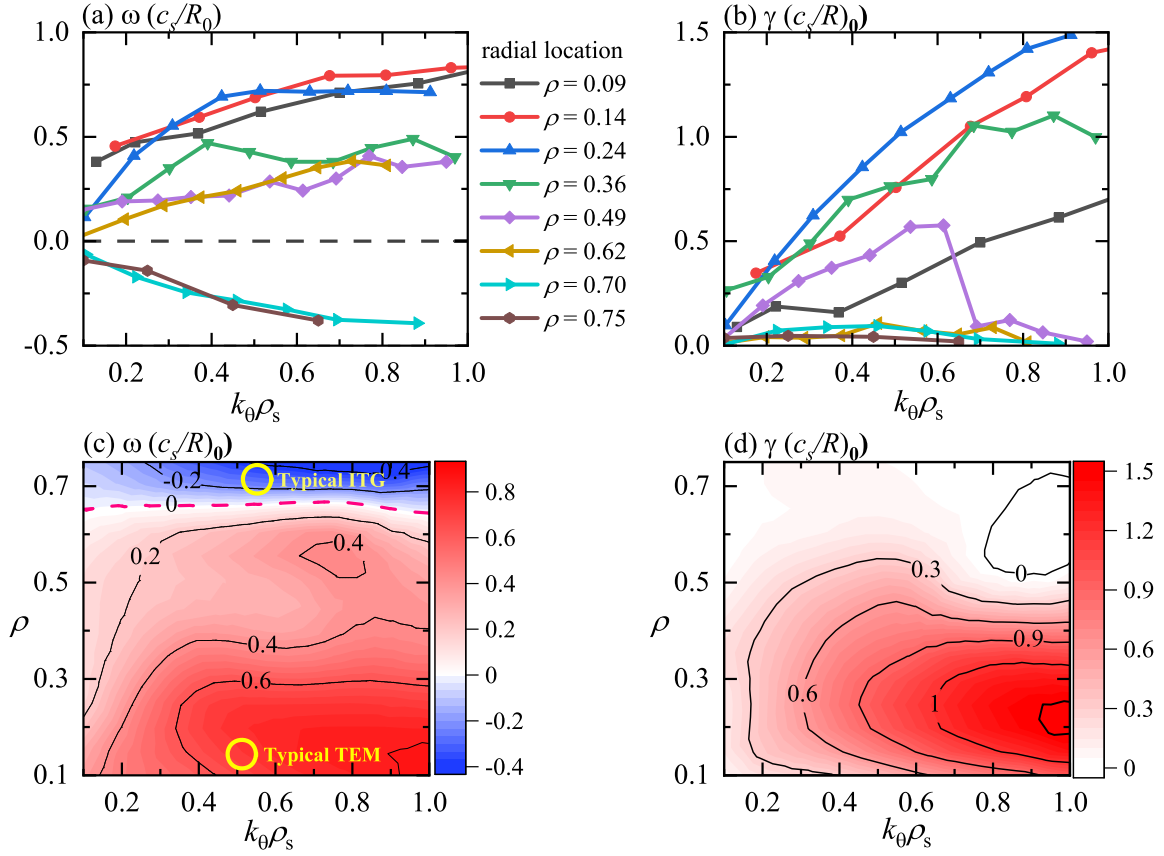


Figure 3. The (a) real frequency and (b) growth rate of dominant instability versus $k_\theta \rho_s$ at different radial locations with experiment profiles. 2D contours of the (c) real frequency and (d) growth rate of dominant instability in the $(k_\theta \rho_s, \rho)$ plane. The dashed pink line in figure 3(c) represents $\omega = 0$.

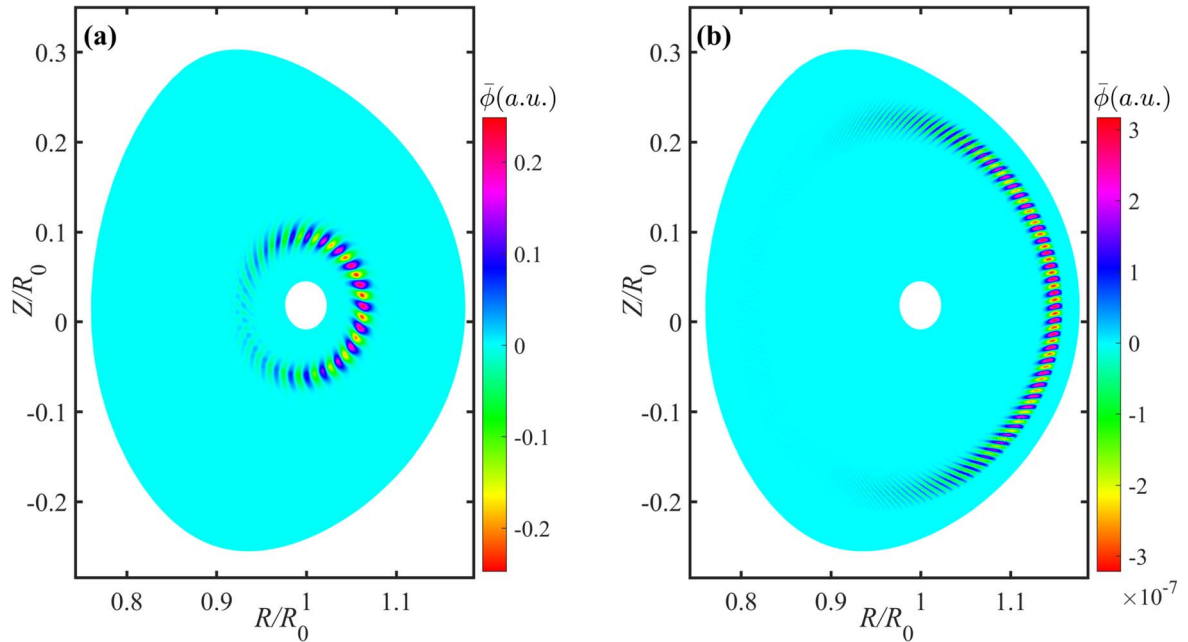


Figure 4. Poloidal cross-sections of the potential fluctuation for (a) typical dominant TEM case and (b) typical dominant ITG instability case.

shown in figure 4(a) and (b), respectively. The parameters for the dominant TEM case are set as $\rho = 0.14$ and $k_\theta \rho_s = 0.50$, the parameters for dominant ITG instability case are set as $\rho = 0.70$ and $k_\theta \rho_s = 0.56$, which correspond to the yellow

circles in figure 3(a). Here, we mention that the fluctuations inside $\rho = 0.66$ are artificially set as zero in figure 4(b) to highlight the mode structure of dominant ITG instability. It is shown that the poloidal cross-sections of potential fluctuation

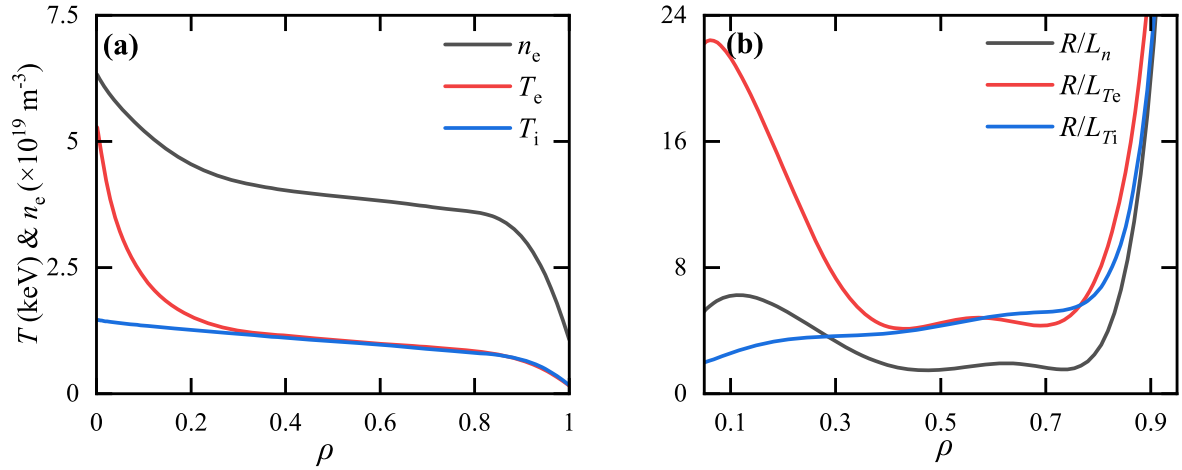


Figure 5. Modified profiles include (a) electron density n_e , electron temperature T_e , and ion temperature T_i , (b) the gradients of modified profiles.

for both dominant TEM and ITG instability present the ballooning mode structure, and are primarily located in the bad curvature region. Though the ITG instability is dominant outside, its magnitude of potential fluctuation is much lower than that of dominant TEM for the same evolution time in the linear simulation, which is due to the fact that the growth rate for ITG instability is much smaller than that for TEM, as shown in figure 3(b).

On one hand, due to the electron temperature in the core being much higher than the ion temperature, its gradient R/L_{T_e} is also higher than R/L_{T_i} . The dominant instability inside is found to be TEM. The ITG instability is strongly stabilized with a relatively small η_i , where $\eta_i = \frac{R/L_{T_i}}{R/L_n}$. On the other hand, the electron temperature and ion temperature around the edge are almost the same. The ITG instability has been found dominant outside since $\eta_i \sim 3$ is larger than its threshold.

To further study how the core peak profiles affect the instability, the modified profiles, including n_e , T_e , and T_i profiles, and their gradients are shown in figure 5. Compared to the profiles shown in figure 2, R/L_{T_e} reaches its maximum of 22.42 at $\rho = 0.07$, closer to the core. Ion and electron temperature profiles and their gradients are nearly the same when $\rho > 0.42$, which is also broader than the experimental profile.

The real frequency and growth rate of dominant instability versus $k_\theta \rho_s$ at different radial locations with modified profiles are given in figures 6(a) and (b), respectively. Alternatively, by interpolating the discrete data shown in figures 6(a) and (b), the 2D contours of real frequency and growth rate in the $(k_\theta \rho_s, \rho)$ plane are obtained and presented in figures 6(c) and (d), respectively. Compared to the results of the experimental profile case in figure 3, the boundary line shifts from around $\rho = 0.66$ to $\rho = 0.54$, which represents that the dominant TEM region narrows while the dominant ITG region broadens. We mention that it may be that the region of discrepancy between R/L_{T_e} and R/L_{T_i} becomes narrower in the modified profiles.

As shown in figure 6(b), the growth rates of dominant TEM on $k_\theta \rho_s$ show different tendencies at different diagnosed radial locations. In detail, when $\rho = 0.10$ and 0.19 , the growth rates increase monotonically as $k_\theta \rho_s$ increases; when $\rho = 0.29$, the growth rates increase monotonically in the region with $k_\theta \rho_s < 0.7$ and then change slightly; when $\rho = 0.40$ and 0.50 , the growth rates increase firstly and then decrease. For a fixed $k_\theta \rho_s$, the growth rates monotonically decrease by enlarging the diagnosed radial location. Note that the dependence of R/L_{T_e} on the diagnosed location in figure 5(b) shows a similar tendency. Analogous to figure 3(b), the TEM under the modified profiles is more unstable with higher R/L_{T_e} . The growth rates of ITG instability at $\rho = 0.60$ and 0.70 are close to the growth rate of TEM at $\rho = 0.50$. Besides, it is also seen that the range of unstable spectrum for ITG instability becomes narrower compared to that for TEM.

The radial location of dominant instability reveals that TEM and ITG instabilities can dominate simultaneously at different radii. The maximum TEM growth rate is located around the place where R/L_{T_e} reaches its maximum. The boundary of the dominant TEM region and dominant ITG instability region hardly changes with $k_\theta \rho_s$ but can be affected by the profile gradient changes. Comparing the results in figures 3 and 6, the growth rate of instability is suppressed, and the strong TEM around the boundary region will be replaced by weak ITG instability because the profile peaks closer to the core.

3.2. Effects of R/L_{T_e} , R/L_{T_i} , and R/L_n on instabilities

The main causes of TEM and ITG instabilities are generally acknowledged to be steep temperature profiles and pressure gradients [47]. In this subsection, the influence of gradients on the destabilized dominant instabilities will be discussed in detail. The diagnosed radial location is set as $\rho_0 = 0.24$, where the maximum growth rate appears. The corresponding parameters are $T_e = 2.48$ keV, $T_i = 1.35$ keV, $T_e/T_i \sim 1.83$, $n_e = 5.26 \times 10^{19} \text{ m}^{-3}$.

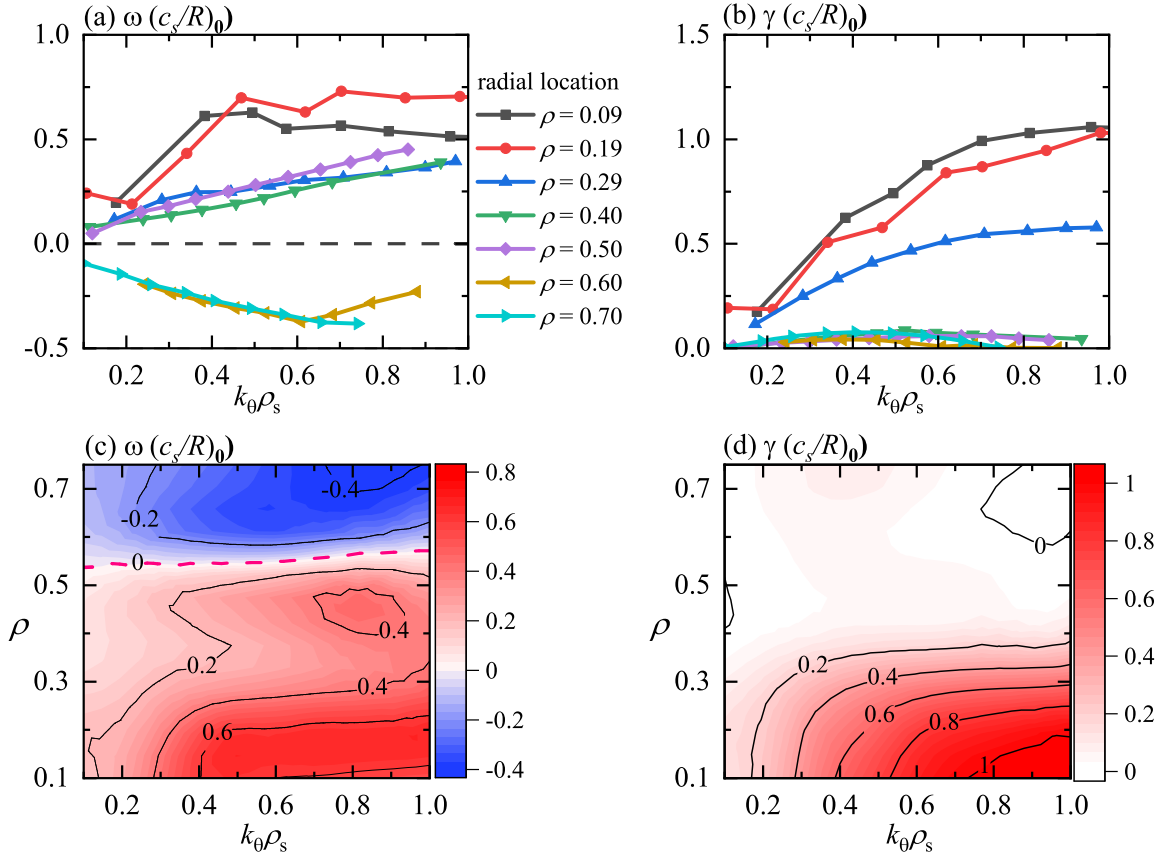


Figure 6. The (a) real frequency and (b) growth rate of dominant instability versus $k_\theta \rho_s$ at different radial locations with modified profiles. 2D contours of the (c) real frequency and (d) growth rate of dominant instability in the $(k_\theta \rho_s, \rho)$ plane. The dashed pink line in figure 6(c) represents $\omega = 0$.

In the GTC linear simulations, the density and temperature profiles are needed. The variations of density and temperature gradients correspond to the variations of density and temperature profiles. In the following simulations on the scanning of density and temperature gradients, the plasma profiles are changed as

$$f'(\rho) = \frac{f^k(\rho)}{f^{k-1}(\rho_0)} \cdot \exp\left(-\left(\frac{\rho - \rho_0}{\Delta\rho}\right)^2\right). \quad (1)$$

Here, $f(\rho)$ stands for the realistic plasma profile, $f'(\rho)$ stands for the modified profile, k is a constant and $\Delta\rho = 4$. It is not hard to find that $f'(\rho_0) = f(\rho_0)$, $R/L_{f'} = kR/L_f$, where $L_f = -[(\partial \ln f)/\partial r]^{-1}$ stands for the scale length of profile f . Thus, the scanning of gradients can be realized by adjusting the parameter k .

The impacts of electron and ion temperature gradients on dominant instability are shown in figure 7. Figures 7(a) and (b) are the real frequency and growth rate spectrum of dominant instability versus $k_\theta \rho_s$, respectively. Here, R/L_{Ti} is fixed at 3.14, while three different R/L_{Te} cases, 2.50, 12.51 and 15.02, are considered. As shown in figure 7(a), the real frequency of TEM increases in the low- k region and keeps unchanged when $R/L_{Te} > 12.51$. However, as R/L_{Te} decreases, the tendency of real frequency increase in the low- k region becomes slow, and the real frequency in the high- k region decreases with $k_\theta \rho_s$, as depicted in the black line. In

figure 7(b), The growth rates of TEM in different cases increase continuously with $k_\theta \rho_s$. For a given $k_\theta \rho_s$, the growth rate of TEM is larger at a higher value of R/L_{Te} , and this tendency is more obvious in the high- k region. Here, TEM dominates in three different cases because that $\eta_i \sim 0.5$ is low, where the ITG instability is strongly suppressed.

Figures 7(c) and (d) show the real frequency and growth rate spectra of dominant instability versus $k_\theta \rho_s$ when R/L_{Te} is fixed at 25.02 and R/L_{Ti} varies from the experimental value of 3.14 to 21.99. When $R/L_{Ti} = 3.14$ and 9.42, the sign of real frequency is positive, indicating that TEM dominates. The real frequency spectra at $R/L_{Ti} = 15.70$ and 21.99 cross zero, indicating the dominant instability transits from TEM to ITG instability. As R/L_{Ti} increases, the ITG instability becomes more unstable. The transition between TEM and ITG instability occurs more easily at higher R/L_{Ti} . The real frequency of TEM decreases with the increment of R/L_{Ti} . When R/L_{Ti} increases, the trend in the high- k region, which is gentle in the experimental profile as the black line, will gradually decrease. The real frequency of ITG instability decreases with $k_\theta \rho_s$. As shown in figure 7(d), the growth rate of TEM, mainly appears in $k_\theta \rho_s < 0.6$, increases with $k_\theta \rho_s$, and it barely changes with R/L_{Ti} . But the growth rate of ITG increases while R/L_{Ti} increases.

In figure 7(c), it seems that the transition between dominant TEM and ITG instability occurs smoothly, which is

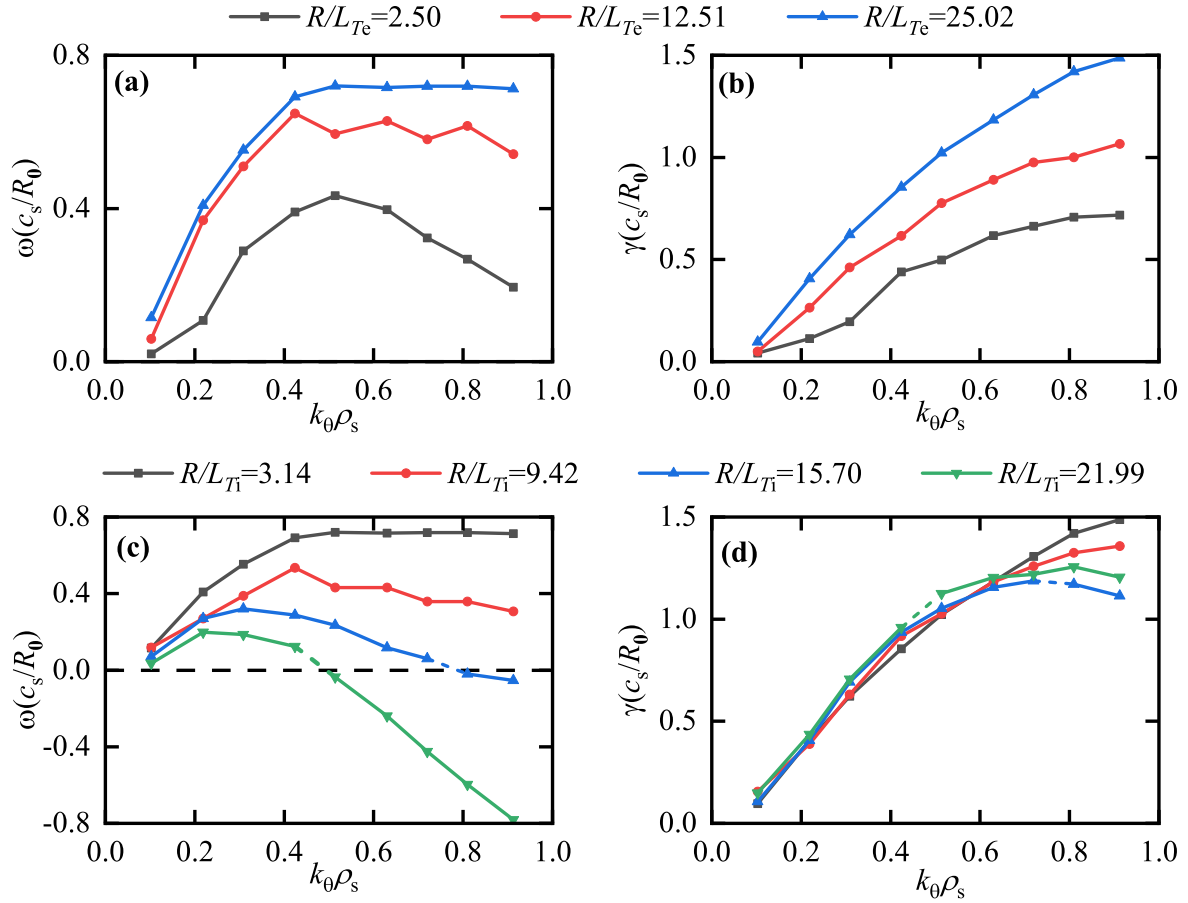


Figure 7. (a) The real frequency ω and (b) the growth rate γ of instabilities while R/L_{Te} varied; (c) the real frequency ω and (d) the growth rate γ of instabilities while R/L_{Ti} varied.

different from the results shown in [42], where a sharp jump between different instabilities is reported. In addition, TEM is also found that it may propagate in the ion diamagnetic drift direction [48]. Thus, it is necessary to clarify whether the negative-frequency mode is ITG or not in figure 7(c). Here, we take $R/L_{Ti} = 21.99$ as an example. We use the adiabatic electron model in GTC. In this situation, only ITG instability can be excited. It is found that the real frequency with $k_\theta \rho_s > 0.4$ is almost unchanged when the electron model changes from non-adiabatic to adiabatic, at the same time, the growth rate drops by about half. It agrees with the character of ITG instability shown in [42]. Similar situations where no sharp jumps between TEM and ITG instability are also reported in [8, 11, 46]. We note that the smooth transition between dominant TEM and ITG instabilities with zero-frequency mode may be due to specific plasma parameters. In [8], it is reported that the zero-frequency mode can be observed in lower impurity ion charge numbers when the driving sources of both TEM and ITG are moderate or strong. In our work, the zero-frequency mode appears in situations with $R/L_{Ti} \geq 15.70$ as shown in figure 7(c).

Figure 8 shows the spectrum of dominant instability when R/L_n varies from 1.38 to 13.76. TEM dominates over the considered range of R/L_n as shown in figure 8(a). The dependence of the real frequency on $k_\theta \rho_s$ is different at different R/L_n : the real frequency in the flat density profile is

proportional to $k_\theta \rho_s$; in the experimental profile, the real frequency increases in the low- k region and stays constant thereafter; in the steep density profile, the real frequency increases in the low- k region and decreases in the high- k region. The growth rate of TEM increases with $k_\theta \rho_s$ at different R/L_n . In addition, a general tendency shows that the growth rate of TEM increases with R/L_n , that is, TEM is destabilized by R/L_n .

To end this subsection, it is concluded that the TEM is destabilized by increasing R/L_{Te} or increasing R/L_n . When R/L_{Ti} exceeds 15.70, the transition between TEM and ITG occurs, especially in the high- k region. In addition, TEM is found to be more sensitive to electron temperature gradients than density gradients. For example, the TEM growth rate increases by 107.3% at $k_\theta \rho_s = 0.91$ when R/L_{Te} increases by ten times in figure 7, but only 52.1% when R/L_n increases by ten times in figure 8.

3.3. Effects of electron-ion temperature rate T_e/T_i

In this subsection, the effects of the electron and ion temperature ratio T_e/T_i at $\rho = 0.24$ on the instabilities are studied. Here, we multiply the experimental temperature profile by a constant to keep the temperature gradients unchanged. The temperature ratio T_e/T_i range is considered from 0.5 to 2.5.

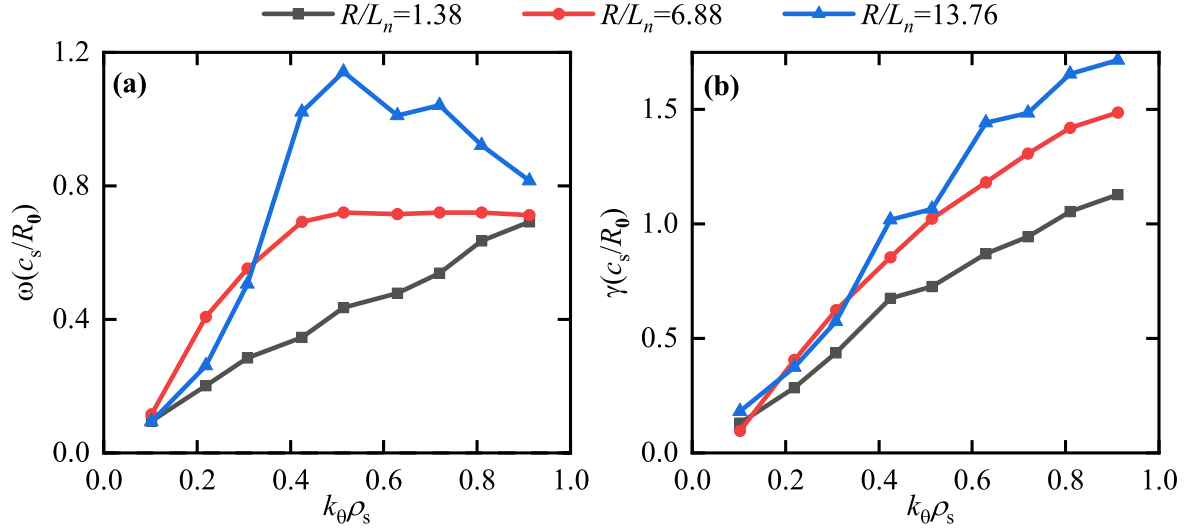


Figure 8. (a) The frequency ω and (b) the growth rate γ of instabilities while R/L_n varied.

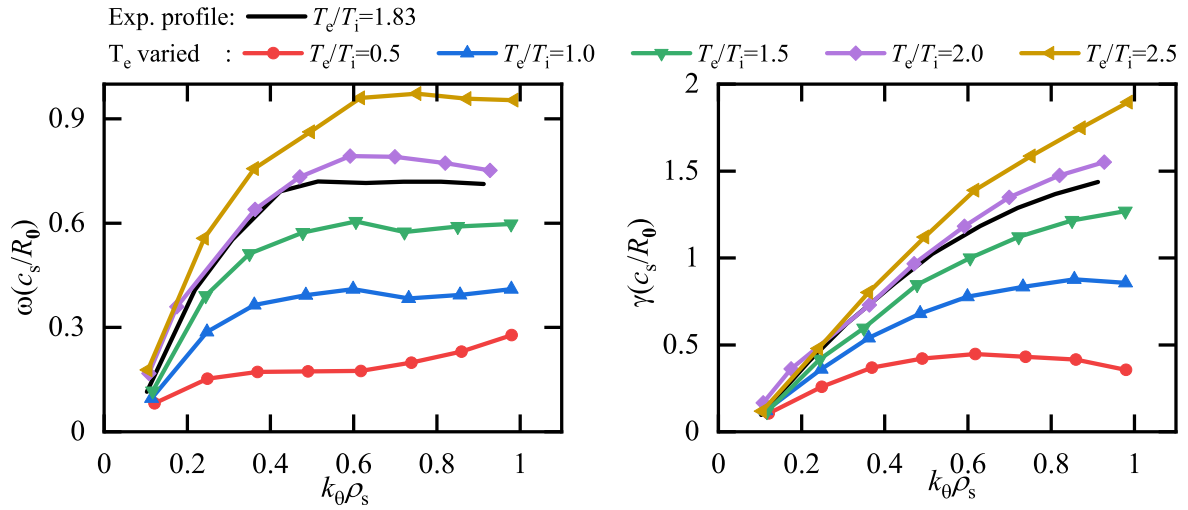


Figure 9. (a) The real frequency ω and (b) the growth rate γ of dominant instability at different T_e/T_i when T_i is fixed while T_e varied. The solid black line represents the results from the experimental profiles.

Figure 9 shows dominant instability spectra at various T_e while keeping T_i fixed. The solid black line is the situation with the experimental temperature ratio $T_e/T_i = 1.83$. As seen in figure 9(a), TEM dominates in considered cases. For a fixed $k_\theta \rho_s$, the real frequency increases with the increase of T_e/T_i . For a given T_e/T_i , the real frequency increases firstly with the $k_\theta \rho_s$, then tends to be stable. The $k_\theta \rho_s$ where real frequency starts to saturate enlarges with the increase of T_e/T_i . For example, it can be found that when $T_e/T_i = 0.5$, the real frequency starts to saturate at $k_\theta \rho_s = 0.25$, when $T_e/T_i = 1.83$, it starts to saturate at $k_\theta \rho_s = 0.48$, and when $T_e/T_i = 2.5$, it starts to saturate at $k_\theta \rho_s = 0.62$. When $T_e < T_i$, the real frequency of TEM slightly increases in the high- k region. In figure 9(b), the growth rate of TEM continuously increases with $k_\theta \rho_s$ when $T_e/T_i > 1.0$. When $T_e/T_i < 1.0$, the growth rate slightly decreases in the high- k region. For a given $k_\theta \rho_s$, a tendency can be seen that γ increases with T_e/T_i , and the increment becomes smaller while T_e/T_i increases. Taking $k_\theta \rho_s = 0.85$ as an example, γ

increases from 0.41 to 0.88 while T_e/T_i changes from 0.5 to 1.0, but it increases from 1.50 to 1.75 while T_e/T_i changes from 2.0 to 2.5.

Figure 10 shows the dominant instability at various temperature ratios T_e/T_i while keeping T_e fixed. The real frequency spectrum of TEM follows a similar pattern, but the changes of ω caused by varying T_i are smaller than the change in ω caused by varying T_e . This phenomenon is even more pronounced in the growth rate spectrum, which is the γ at different T_e/T_i almost overlapped in figure 10(b).

The results above show that temperature ratios T_e/T_i can destabilize TEM instability, which is consistent with experimental and theoretical evidence. It is shown that the growth rate of TEM significantly changes with electron temperature T_e , but barely changes with ion temperature T_i , which agrees well with the results in [1]. An explanation is given that the dispersion relation of TEM is related to the electron diamagnetic drift velocity, which is affected by electron temperature rather than ion temperature [36].

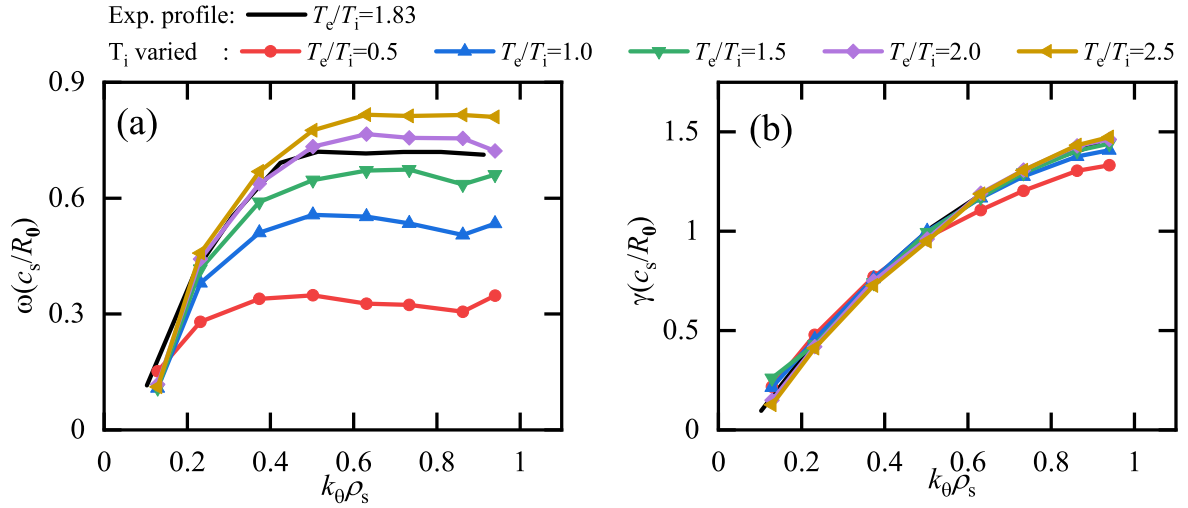


Figure 10. (a) The real frequency ω and (b) the growth rate γ of dominant instability at different T_e/T_i when T_e is fixed while T_i varied. The solid black line represents results from the experimental profiles.

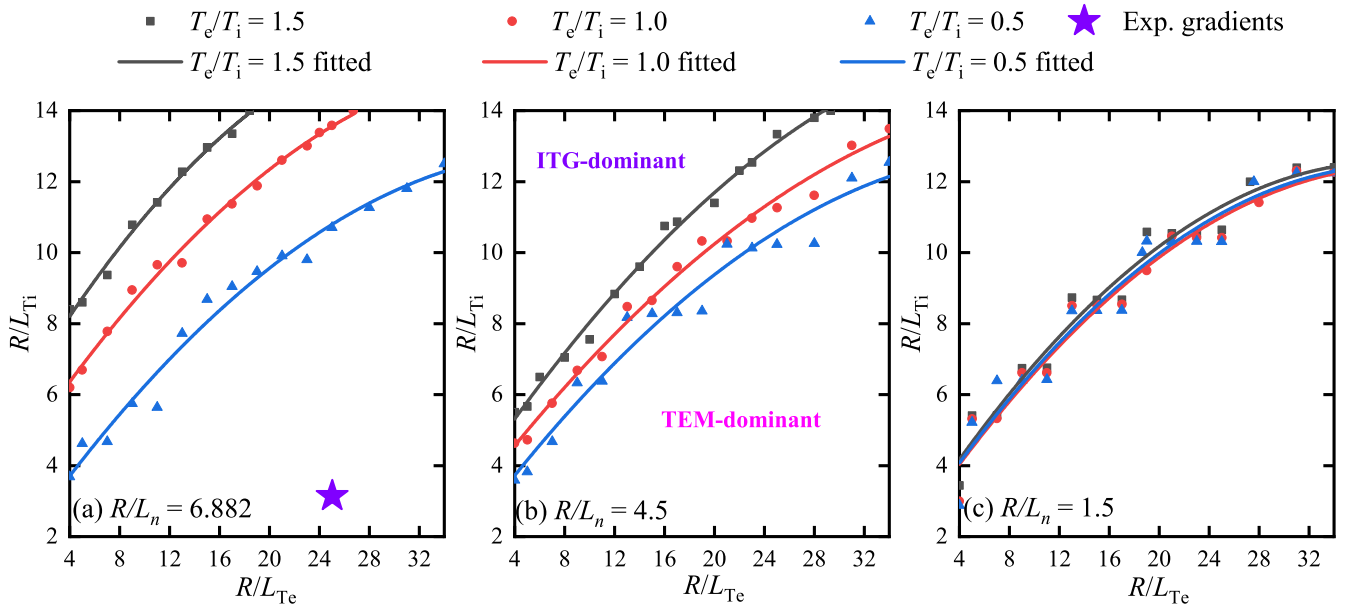


Figure 11. Dominant instability diagrams at different ratios T_e/T_i calculated with a single wave number, (a) $R/L_n = 6.88$, (b) $R/L_n = 4.50$ and (c) $R/L_n = 1.50$. The star represents the experimental profile value.

4. Dominant instability diagrams

To further study the effects of temperature gradient on the transition of TEM and ITG instability, the dominant instability diagrams on the regions with $R/L_{Te} = 2-14$ and $R/L_{Ti} = 4-34$ are presented in figure 11. Three different values of $R/L_n = 6.88, 4.50$ and 1.50 are adopted. For each R/L_n , the temperature ratios $T_e/T_i = 1.5, 1.0$ and 0.5 are considered by varying T_e while T_i is fixed. The simulations are performed by diagnosing a single wave number $n = 42$ at $\rho = 0.24$ in different plasma profiles. The experimental value is marked by the star in figure 11(a). Note that the instability in the lower temperature gradient region with $R/L_{Te} < 2$ and $R/L_{Ti} < 4$ is too weak to be considered here.

The dots represent $\omega = 0$. Note that the real frequency of zero is not directly obtained from the GTC electrostatic

simulation. For a fixed R/L_{Te} , the dominant instability can transit from TEM to ITG instability by increasing R/L_{Ti} , which corresponds to the transition of the sign of real frequency from positive to negative. The real frequency of zero results from the linear interpolation of the positive real frequency of dominant TEM and the negative real frequency of dominant ITG instability. Note that the interpolation is manipulated around the parameters where the transition occurs. Alternatively, the curves are fitted based on the dots to represent the separation of dominant TEM and ITG instability, namely, ITG instability dominates above the curve, and TEM dominates below.

Figure 11(a) summarizes the scan results with experimental density profile $R/L_n = 6.88$. The curves separating the dominant TEM and ITG instability region are quadratic. For a fixed R/L_{Te} , increasing R/L_{Ti} to cross the curve causes a

dominant instability transition from TEM to ITG instability. On the contrary, increasing R/L_{Te} to cross the curve causes a dominant instability transition from ITG to TEM for a fixed R/L_{Ti} . This pattern explains that the dominant instability transits from TEM to ITG instability in figure 7(c) when R/L_{Ti} reaches 15.70. Meanwhile, the curve moves upward as the temperature ratio increases, that is, the dominant ITG instability region narrows while the dominant TEM region broadens. Due to the destabilization of ITG when T_e/T_i increases [37], a higher R/L_{Ti} is needed to drive the dominant instability transition from TEM to ITG instability for a given R/L_{Te} .

Different density gradients within the scope of the experimental density profile are considered, imposing $R/L_n = 4.50$ and $R/L_n = 1.50$, as shown in figures 11(b) and (c). Also, the fitted curves for different T_e/T_i and R/L_n are quadratic. By comparing the three figures, one can conclude that the decrement of R/L_n can weaken the effects of T_e/T_i . The curve slides downwards as the density gradient R/L_n decreases, and the decrement is more obvious in a large temperature ratio. Here we fix $R/L_{Te} = 8.0$ for example, for $T_e/T_i = 1.5$, dominant TEM transition to ITG instability occurred around $R/L_{Ti} = 10$ when $R/L_n = 6.88$, but transition occurred around $R/L_{Ti} = 6$ when $R/L_n = 1.50$; for $T_e/T_i = 0.5$, dominant TEM transition to ITG instability occurred around $R/L_{Ti} = 6$ when both $R/L_n = 6.88$ and $R/L_n = 1.50$. The change in $T_e/T_i = 0.5$ in three cases is negligible, which indicates that the dominant TEM region is almost independent of density gradient R/L_n at low T_e/T_i . Also, it can be seen that the boundary curves with different temperature ratios almost overlap with each other when $R/L_n = 1.50$. Namely, the temperature ratio barely affects the dominant instability transition in a flat-density profile.

5. Conclusions and discussions

In conclusion, dependencies of the dominant electrostatic instability on plasma parameters are investigated based on a real discharge in the EAST steady-state scenario. The properties of radial locations of dominant instability show that TEM and ITG can coexist simultaneously but dominate at different radii. TEM dominates inside, and ITG dominates outside. The TEM with the maximum growth rate appears around the radial position where the maximum R/L_{Te} is located. By modifying the plasma profiles artificially to make R/L_{Te} peak close to the core, the dominant TEM region moves correspondingly. The growth rate of instability is also suppressed because the profile peaks closer to the core.

The scanning of the plasma parameters is carried out at $\rho = 0.24$, where R/L_{Te} reaches its maximum. The R/L_{Te} scanning shows that TEM dominates in a wide range with $R/L_{Te} = 2.50$ – 25.02 , the larger the R/L_{Te} is, the more unstable the TEM is. The R/L_{Ti} scanning shows that TEM dominates when $R/L_{Ti} < 9.42$. It is also found that ITG may dominate over TEM when R/L_{Ti} approaches R/L_{Te} . When $R/L_{Ti} > 15.70$, the dominant instability in the high- k region transits from TEM to ITG. TEM is dominant in the region

with $R/L_n = 1.38$ – 13.76 and is destabilized by R/L_n . In addition, TEM is found to be more sensitive to temperature profile than density profile. Further, studies on electron-ion temperature ratio demonstrate that TEM is destabilized by T_e/T_i , besides, TEM is more sensitive to the variation of T_e compared to the variation of T_i .

Dominant instability diagrams in $(R/L_{Te}, R/L_{Ti})$ plane are numerically obtained, as shown in figure 11. The curves represent the boundary of the TEM-dominant region and ITG-dominant region in different T_e/T_i and R/L_n . It is found that individually decreasing R/L_{Te} or increasing R/L_{Ti} can lead to a transition from TEM to ITG. The higher T_e/T_i can broaden the region of dominant TEM. With decreasing R/L_n , those curves move downward, which indicates that the ITG-dominant region becomes wider. When $R/L_n = 1.5$, the boundary curves with different temperature ratios almost overlap with each other. It is indicated that the effects of T_e/T_i on the transition of TEM and ITG become weaker by the decrement of R/L_n . With the help of figure 11, one may easily predict the dominant electrostatic instability in the corresponding parameter range.

To the end, we mention that the scanning in this work reveals that the temperature gradient is a non-negligible factor in the transition of dominant electrostatic instability, such as the results presented in figures 3 and 6, where the experimental profiles and artificially modified profiles are adopted, respectively. It should be noted that the mode transition is also affected, for instance, by the fast ions, collisions, and rotational effects. We have found that electron collision effects are important in nonlinear simulation in previous work [30]. It is an attractive question to systematically research the dominant turbulence transition with considering the fast ions and collision effects, etc. We leave this issue for future work.

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