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To cite this article: Jinghong FENG *et al* 2026 *Plasma Sci. Technol.* **28** 065101

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Linear gyrokinetic simulation of fast-ion effects on the transition of the dominant electrostatic instability from TEM to ITG in EAST

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Received 13 October 2025, revised 12 March 2026

Accepted for publication 12 March 2026

Published 19 June 2026



Abstract

Linear gyrokinetic simulations have been performed using the gyrokinetic toroidal code (GTC) code to investigate the effects of fast ions on the dominant instability changes from trapped electron mode (TEM) to ion temperature gradient (ITG) in the EAST. The effects of fractions (5%, 7.5% and 10%) and temperatures (10 keV, 20 keV and 30 keV) of fast ions are investigated. The dominant mode transitions from TEM to ITG mode under different plasma parameters. A transition of the dominant instability is observed at $0.7 \leq k_{\theta}\rho_s \leq 0.8$ and shifts to $k_{\theta}\rho_s \approx 0.7$ when fast ions are considered. In addition, fast ions stabilize ITG modes, and the effect becomes more significant as the fraction of fast ions increases, reducing the growth rate by approximately 10% when the fraction of fast ions is 10%. The stabilizing effect increases with increasing temperature of fast ions, but varies little for $T_f > 20$ keV. Fast ions reduce the ion temperature gradient R/L_{T_i} threshold of the dominant instability changes from TEM to ITG. The threshold decreases with decreasing temperature of fast ions, with a reduction of about 10%–20% when the fraction reaches 10% in hydrogen plasmas, and about 3%–12% when deuterium is the main ion. Furthermore, the normalized electron temperature gradient R/L_{T_e} for the dominant instability changes from ITG to TEM is lower in hydrogen plasmas, decreasing from 5.4 to 4.1 as T_f increases from 10 keV to 30 keV, while in deuterium plasmas it decreases from 10.5 to 9.5. Moreover, electron-electron collisions lead to the dominant instability changes from TEM to ITG at $0.4 \leq k_{\theta}\rho_s \leq 0.8$ and strongly stabilize the ITG mode, reducing its growth rate about 50%, while ion-ion collisions have little influence on TEM and ITG.

Keywords: gyrokinetic simulation, fast ions, collision effects, microinstabilities

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

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1. Introduction

In magnetic confinement fusion, improving energy and particle confinement remains a critical challenge. However, anomalous transport associated with turbulence leads to the degradation of energy confinement. The trapped electron mode (TEM) [1] and ion temperature gradient (ITG) mode [2] are recognized as key drivers of turbulence [3, 4] and primary causes of heat transport [5]. It has been demonstrated that microinstabilities, such as TEM and ITG, can coexist [6, 7] under certain conditions, with their dominant roles undergoing transitions depending on plasma parameters [8–11]. Microinstabilities are influenced by various factors, including electron and ion temperature gradients [12], magnetic shear [13], fast ions [14], and collision effects [7]. Investigating the transition mechanisms between TEM and ITG and their relation to plasma parameters is essential for understanding anomalous transport [15–17].

A transition of the dominant instability from TEM to ITG at $k_\theta \rho_i \approx 0.6$ (k_θ is the poloidal wave number and ρ_i is the ion Larmor radius) is observed as the ion temperature gradient R/L_{T_i} increases, when kinetic electron effects are included under Cyclone Base Case (CBC) parameter conditions [18]. Linear and nonlinear simulations performed with the Gyrokinetic Electromagnetic Numerical Experiment (GENE) code have demonstrated that TEM and ITG can coexist [6]. The outward transport induced by TEM and the inward transport driven by ITG can dynamically balance at different values of perpendicular wavenumber $k_\perp$ resulting in zero net flux. An empirical criterion for predicting the dominant instability type has been proposed based on experimental data in the HL-2A tokamak [19]. When the dominant instability is ITG or ∇T_e -TEM in the electron density gradient R/L_n range of $1.0 < R/L_n < 7.0$, the instability type can be described by the relation $R/L_{T_i} + R/L_n - R/L_{T_e}$. Specifically, when $R/L_{T_i} + R/L_n - R/L_{T_e} \geq 7.0$, ITG is the dominant mode, otherwise TEM becomes the dominant mode. In ASDEX-Upgrade, modulation of ECRH power reveals that an increase in plasma collisionality induces a transition of the dominant instability from TEM to ITG, significantly reducing thermal transport levels [20]. The effect of collisions on the dominant instability has been investigated, revealing that the growth rate of collisionless trapped electron mode (CTEM) is decreased by collisions through the reduction of the response of trapped electrons. This stabilizing effect is more significant for temperature-gradient-driven CTEM, whereas density-gradient-driven CTEM shows less sensitivity to collision effects [21]. The destabilization of CTEM is primarily driven by R/L_{T_e} and R/L_n , while collision effects provide a significant stabilizing influence, as shown by GTC simulations of high- β_p discharges on EAST. A TEM/ITG hybrid mode is suggested to exist at $k_\theta \rho_s < 0.38$, and the transition to ITG appears as R/L_{T_i} increases, consistent with adiabatic electron simulations showing maximum ITG growth at $k_\theta \rho_s = 0.7 - 0.8$ [22]. The dominant instability shifts from TEM to ITG as R/L_{T_e} decreases or R/L_{T_i}

increases, and the effect of T_e/T_i on this transition becomes weaker with decreasing R/L_n [23]. In the ASDEX-Upgrade, the effect of energetic particles (EPs) on the transition of dominant microinstabilities has been investigated using the linear gyrokinetic code GS2. The results show that, as the fraction of EPs increases, the growth rate of the ITG gradually decreases and is completely suppressed when $n_i/n_e \approx 0.35$, indicating a classical dilution effect of the main ions. When the fraction of EPs increases beyond $n_i/n_e > 0.6$, the growth rate rises again due to the excitation of TEM, suggesting a transition of the dominant instability from ITG to TEM [24].

In this work, linear gyrokinetic simulations have been performed using the GTC code to investigate the effects of fast ions parameters on the transition of dominant microinstabilities in the EAST. This work uses linear gyrokinetic simulations to study the effects of fast ions on plasma microinstabilities. The analysis focuses on fast-ion dilution and changes in the trapped-electron response, which affect the dominant electrostatic instability at the linear level. Nonlinear effects and their impact on turbulent transport are not addressed and are left for future work. The structure of the paper is as follows. In section 2, the typical parameters in EAST and the simulation setup are introduced. In section 3, linear gyrokinetic simulations are carried out to study the influence of fraction and temperature of fast ions on the transition of the dominant instability, as well as the corresponding R/L_{T_i} and R/L_{T_e} of the transition of the dominant instability. Discussion and conclusion are presented in section 4.

2. Typical parameters in EAST and simulation parameter settings

EAST is characterized by a major radius of $R_0 = 1.9$ m, a minor radius of $a = 0.45$ m, and a central toroidal magnetic field of $B_T = 2.4$ T. In this study, the EAST typical plasma parameters are adopted for the simulations. The typical radial profiles of electron density n_e , electron temperature T_e , ion temperature T_i , and safety factor q are shown in figure 1(a), and the corresponding profiles of the normalized electron density gradient R/L_n , normalized temperature gradients for both electrons R/L_{T_e} and ions R/L_{T_i} , and magnetic shear are also shown in figure 1(b). The normalized electron temperature gradient reaches its maximum at $\rho = 0.24$ (ρ is the normalized poloidal flux), where $R/L_{T_e} = 24.08$, significantly larger than the ion temperature gradient $R/L_{T_i} = 3.14$ at the same location. In the outer region ($\rho > 0.57$), the electron and ion temperature gradients are nearly equal.

For linear simulations, the main ion species is chosen to be either hydrogen (H) or deuterium (D). The diagnostic location is $\rho_0 = 0.24$, and the simulation domain covers the radial range from $\rho = 0.14$ to $\rho = 0.39$. The radial region $\rho = 0.14 - 0.39$ is selected because the electron temperature gradient is radially symmetric in this interval. The diagnostic location $\rho = 0.24$ is chosen because it corresponds to the maximum of the electron temperature gradient R/L_{T_e} , which

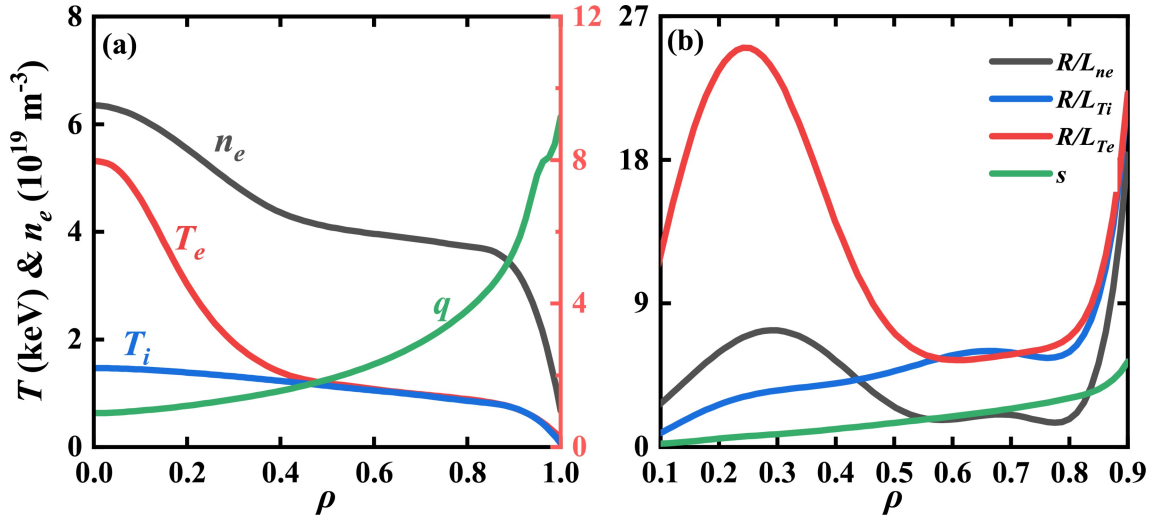


Figure 1. Typical plasma parameters profiles in EAST. (a) Electron density and temperature, ion temperature, and safety factor q ; (b) normalized density gradient R/L_n , electron temperature gradient R/L_{T_e} , ion temperature gradient R/L_{T_i} , and magnetic shear s profiles.

is the main drive for the TEM. The simulation time step t_{step} is $0.02 R_0/c_s$, where $c_s = \sqrt{T_{e0}/m_i}$, T_{e0} is the on-axis electron temperature, and m_i is the ion mass. The radial and poloidal grid points are adjusted at $\rho = 0.24$ so that the grid length is comparable to the ion gyro-radius. Impurities are represented by a fixed effective charge of $Z_{\text{eff}} = 2.2$, without considering individual species.

In this work, linear simulations are performed by GTC. GTC is a global three-dimensional particle-in-cell (PIC) code used to describe marker particles [25]. Ions are treated using the gyrokinetic formalism, while electrons are modeled by a fluid-kinetic hybrid approach to improve computational efficiency [26]. This hybrid model decomposes the electron perturbed distribution function into a low-order adiabatic component and a higher-order non-adiabatic component. The lower order (adiabatic part) of the electronic response is described as a massless fluid and is solved by continuity equations, while the higher order (non-adiabatic part) is solved by gyrokinetic equations with all nonlinear effects remaining. Exploiting the symmetry of the tokamak configuration, magnetic flux coordinates, also known as Boozer coordinates, defined as $Z = (\psi, \theta, \zeta)$, are adopted in GTC [27], where ψ is the poloidal flux, θ is the poloidal angle, and ζ is the toroidal angle. The gyrokinetic equation is given in equation (1).

$$(\partial_t + \dot{\mathbf{X}} \cdot \nabla_{\mathbf{X}} + \dot{v}_{\parallel} \partial_{v_{\parallel}} - C_{\alpha}) F_{\alpha}(\mathbf{X}, v_{\parallel}, \mu, t) = 0, \quad (1)$$

where $\alpha = i, e$ indicates the particle species, $v_{\parallel}$ denotes the velocity component parallel to the magnetic field and C_{α} is the collision operator for species α . The magnetic moment is given by $\mu = mv_{\perp}^2/(2B)$, where $v_{\perp}$ is the perpendicular velocity. $\mathbf{X}$ denotes the guiding-center position of a particle.

The core principle of the δf algorithm is to split the distribution function into an equilibrium part f_0 and a perturbation δf , only the evolution of δf is followed in the particle simulation. If $\delta f \ll f_0$, the numerical noise is greatly reduced. The distribution function is expressed as $f_{\alpha} = f_{0\alpha} + \delta f_{\alpha}$ for species α and $\mathbf{B} = \mathbf{B}_0 + \delta \mathbf{B}$. From equation

(1), the gyrokinetic equation for the equilibrium part becomes:

$$\begin{aligned} \frac{df_{0\alpha}}{dt} &= \frac{\partial f_{0\alpha}}{\partial t} + (v_{\parallel} \mathbf{b}_0 + \mathbf{v}_d) \cdot \nabla f_{0\alpha} - \frac{\mu}{m_{\alpha}} \frac{\mathbf{B}_0^*}{B_0} \cdot \nabla B_0 \frac{\partial f_{0\alpha}}{\partial v_{\parallel}} - C_{\alpha}(f_{0\alpha}) \\ &= 0. \end{aligned} \quad (2)$$

Here, $\mathbf{b}_0 \equiv \mathbf{B}/B_0$ defines the unit vector along the equilibrium magnetic field $\mathbf{B}_0$, and B_0 is its magnitude. The magnetic drift velocity $\mathbf{v}_d = v_{\parallel}^2/\omega_c \mathbf{b}_0 \times (\nabla \times \mathbf{b}_0) + \mu/(m\omega_c) \mathbf{b}_0 \times \nabla B$, where ω_c is the cyclotron frequency. To balance accuracy and efficiency, a Monte Carlo collision scheme with a simplified Fokker-Planck operator is employed, where key approximations are justified for capturing the dominant collisional effects on trapped particles in GTC [28]. The simplified Fokker-Planck operator reduces the original bounce-averaged integral over three-dimensional velocity space and time, thereby significantly decreasing the computational cost.

The electron plasma beta ($\beta_e = \frac{8\pi n_e T_e}{B^2}$) in our simulations is 0.89%. Because the electron temperature and density are fixed, β_e remains constant. Electromagnetic linear simulations give growth rates only a few percent different from the electrostatic results when fast ions are included. This shows that the electrostatic model captures the main physics. Therefore, the electrostatic approximation is used to reduce computational cost.

3. Simulation results

3.1. Effects of fast ions on the dominant TEM instability

The following collisionless simulations are performed, hydrogen is the main ion, the fractions of fast deuterium ions (n_i/n_e) are 5%, 7.5% and 10%, with a fixed temperature of $T_i = 20$ keV, and a slowing-down distribution for the fast ions. The normalized temperature and density gradients of

fast ions are $R/L_{T_i} = R/L_{T_e} = 24.08$ and $R/L_{n_i} = R/L_{n_e} = 6.80$, respectively. Sensitivity analysis shows that the growth rate of the dominant mode changes by less than 5% when R/L_{T_i} varies between 10 and 30 [29]. This assumption captures the essential physics while keeping the simulations computationally efficient. In this section, the bulk ion temperature and density gradients are fixed at $R/L_{T_i} = 2.31$ and $R/L_{n_i} = 6.80$, and quasi-neutrality equation $n_e = n_i + Z_i n_f$ is maintained in the simulation. The real frequency ω and growth rate γ versus $k_\theta \rho_{s,H}$ are presented in figure 2. Both the real frequency and growth rate are normalized to c_s/R_0 , corresponding to approximately 27.27 kHz. $\rho_{s,H}$ is the thermal hydrogen ion gyro radius. In this work, modes with positive (negative) real frequencies propagate in the electron (ion) diamagnetic direction.

The real frequency of the dominant TEM initially increases significantly with $k_\theta \rho_{s,H}$, and then gradually saturates, as shown in figure 2. With the increase of fraction of fast ions, the real frequency of the dominant TEM decreases. The growth rate of the dominant TEM increases notably with $k_\theta \rho_{s,H}$. The stabilizing effect of fast ions on the dominant TEM remains weak and shows little sensitivity to the fraction of fast ions. Changes in the fraction of fast ions have a negligible effect on the linear growth rate of the dominant ∇T_e -TEM, which decreases gradually by less than 5% as the fraction increases from 0% to 10%, as shown in figure 2(d). The simulation of electron temperature gradient (R/L_{T_e}) is also performed, showing that the TEM is mainly driven by R/L_{T_e} . In this study, $R/L_{T_e} = 24.08$, and the mode is ∇T_e -TEM.

To further study the influence of fast ions on the ∇n_e -TEM, the density gradient is $R/L_n = 13.5$, while the electron and ion temperature gradients are reduced to $R/L_{T_e} = 2.39$ and $R/L_{T_i} = 1.53$, with 5% and 10% fractions, and fixed fast ions parameters $R/L_{T_i} = 24.08$. The real frequency and growth rate versus $k_\theta \rho_{s,H}$ are shown in figure 3. The dominant TEM is slightly destabilized by fast ions, and the maximum growth rate increases to $\gamma_{\text{TEM,max}} = 2.04 c_s/R_0$ from $1.92 c_s/R_0$ without fast ions, an increase of approximately 6%, when the fraction of fast ions is 10%. Fast ions destabilize the ∇n_e -TEM, enhancing the instability by increasing the number of electrons resonating with the drift waves.

To isolate the influence of fast ions on different TEM (∇T_e -TEM and ∇n_e -TEM), collisionless simulations were performed considering fast deuterons with a temperature of $T_f = 20$ keV. Two distinct density fractions, $n_f/n_e = 5\%$ and 10% are considered in the simulations, the results are presented in figure 4. The stabilization of the mode is systematically enhanced by increasing the fraction of fast ions when it is a ∇T_e -TEM [30–32]. Fast ions stabilize the dominant ∇T_e -TEM within the range of $3 < R/L_{n_e} < 10$, whereas they destabilize it at $R/L_{n_e} > 10$, where the mode becomes a ∇n_e -TEM [33]. This indicates a drive dependent dual role of fast ions in TEM regulation.

3.2. Effects of collisionality on the dominant TEM instability

Under the conditions of $T_f = 20$ keV and 10% fraction of fast deuterium ions, with electron–electron collisions included, the real frequency and growth rate of the dominant

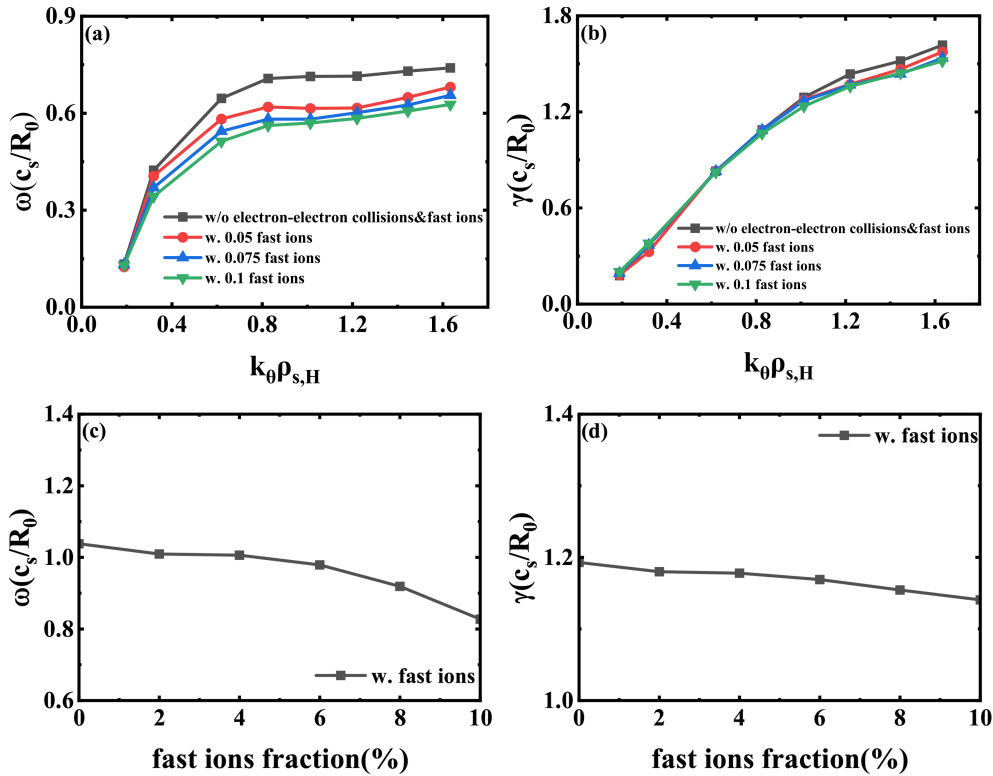


Figure 2. Effect of fast ions on (a) the real frequency ω and (b) the growth rate γ of the dominant instability when the main ion is hydrogen. Results for $T_f = 20$ keV and 5% (red line), 7.5% (blue line) and 10% (green line) fractions; (c) and (d) show ω and γ versus fraction of fast ions, respectively. the black line represents the case without fast ions.

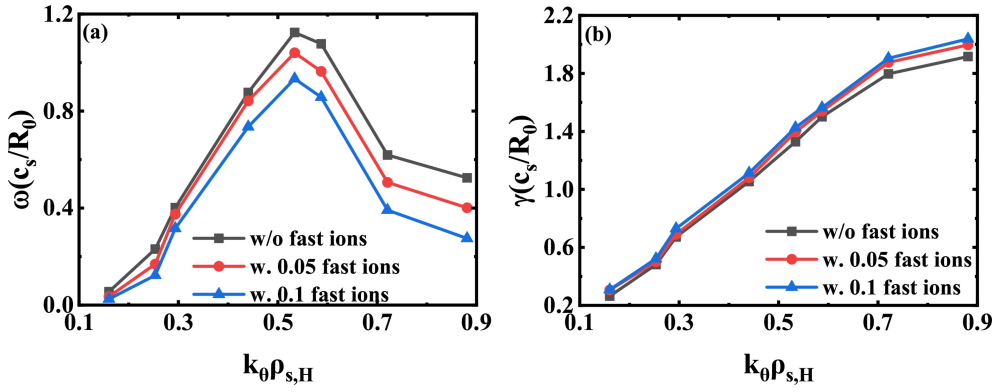


Figure 3. Effect of fast ions on (a) the real frequency ω and (b) growth rate γ of the TEM dominated instability when the main ion is hydrogen, with $R/L_{Te} = 2.39$, $R/L_{Ti} = 1.53$, and $R/L_n = 13.5$. The red and blue lines correspond to fast-ion fractions of 5% and 10%, respectively, while the black line denotes the case without fast ions.

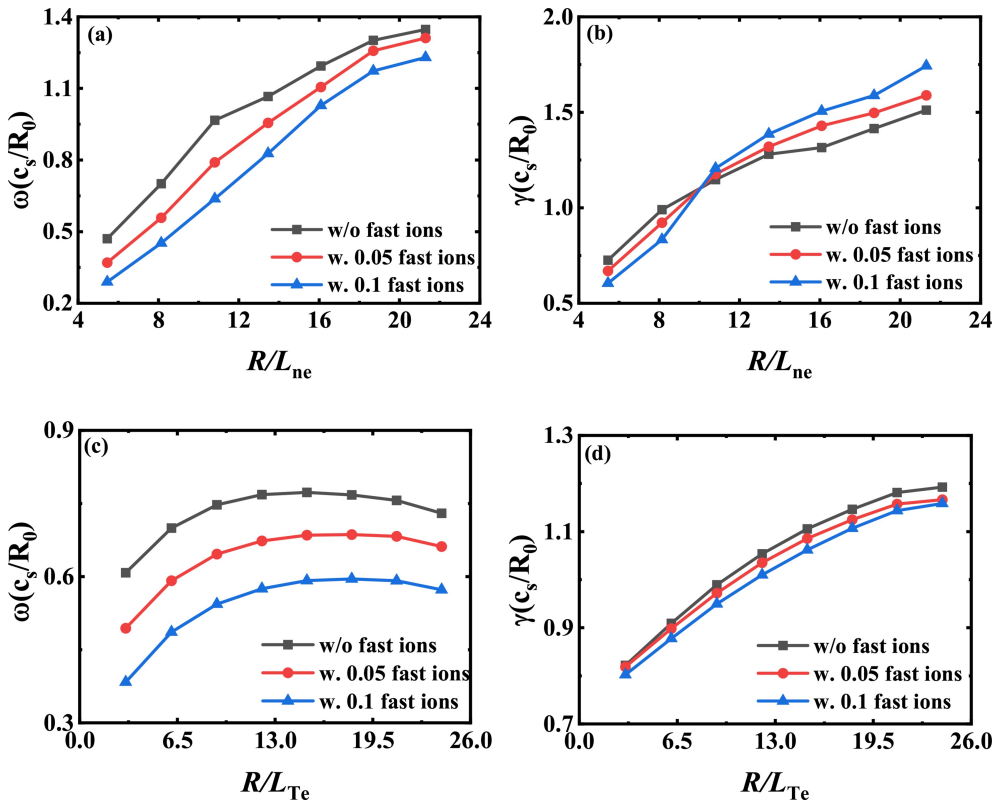


Figure 4. Effects of fast ions on ((a), (c)) the real frequency ω and ((b), (d)) growth rate γ are shown under different R/L_{Te} and R/L_{ne} conditions for main ions of hydrogen. The black line represents the case without fast ions.

instability versus $k_\theta \rho_{s,H}$ are presented in figure 5. The mode is identified as ∇T_e -TEM. Simulations including ion-ion collisions are also performed. The results show that ion-ion collisions have little effects on the dominant instability. Therefore, the corresponding results are not shown.

The real frequency increases compared to the collisionless case when electron-electron collisions are included, as shown in figure 5(a). The growth rate decreases significantly when electron-electron collisions are included. It is reduced to approximately 70%, as shown in figure 5(b). These results suggest that electron-electron collisions stabilize the TEM dominated instability.

Based on the EAST typical parameters, the corresponding collision frequencies are $\nu_{ee} = 0.79 c_s/R_0$ and $\nu_{ii} =$

$0.03 c_s/R_0$, respectively. The electron-electron collision frequency is much higher than the ion-ion collision frequency. The real frequency of the dominant TEM is on the same order of magnitude as ν_{ee} , indicating that electron-electron collisions reduce the response of trapped electrons and thereby stabilize the TEM. Collision effects are found to suppress the resonance mechanism of trapped electrons, weaken the TEM drive, and consequently reduce the instability.

3.3. Effects of fast ions on the transition of dominant instability

To investigate the transition of the dominant instability, the

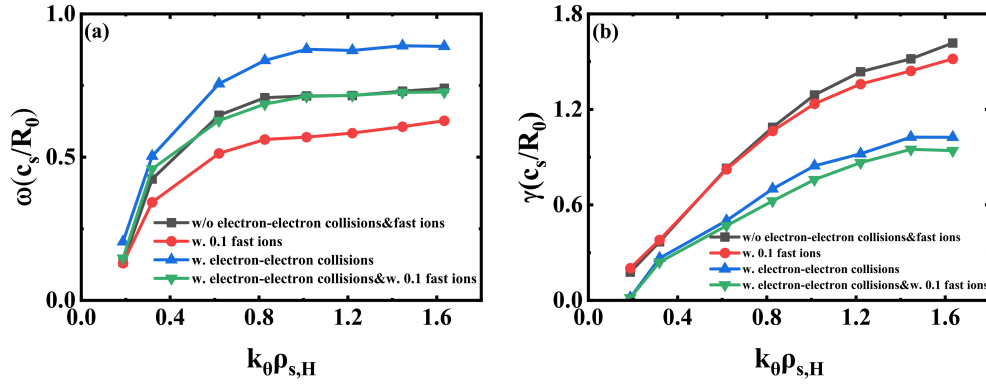


Figure 5. Effect of electron–electron collision (blue and green lines) on (a) the real frequency ω and (b) growth rate γ . The black line indicates the case without fast ions and collision effect, while the red line represents the case with fast deuterium ions with $T_f = 20$ keV and 10% fraction.

normalized ion temperature gradient R/L_{T_i} is increased to 21.9. The simulation domain is $\rho = [0.14, 0.39]$, with the diagnostic location at $\rho_0 = 0.24$, where the ion temperature is $T_i = 1.37$ keV. All other profile parameters remain consistent with those in figure 1. In these subsections, the effects of fraction and temperature of fast ions, as well as electron and ion temperature gradients on the dominant microinstabilities are investigated without considering collisional effects.

3.3.1. Effect of fraction n_f/n_e Linear simulations are carried out by introducing fast deuterium ions with a fixed temperature of $T_f = 20$ keV with different fractions (5%, 7.5% and 10%). The main ions are taken as either hydrogen or deuterium for comparison. The real frequency and growth rate versus $k_\theta \rho_{s,H/D}$ are calculated, as shown in figures 6(a)–(d), respectively.

The change of the main ion species has only little effects on the trends of the real frequency and growth rate. This behavior is mainly due to the stronger influence of the background plasma charge number, while the mass number has relatively little effects.

The transition of the dominant instability is observed around $k_\theta \rho_{s,H} = 0.8$ and $k_\theta \rho_{s,D} = 0.75$, as shown in figures 6(a) and (c). Transition of the dominant instability is observed at lower $k_\theta \rho_{s,H}$ ($k_\theta \rho_{s,D}$) as the fraction of fast ions increases, with the transition identified around $k_\theta \rho_{s,H} = 0.7$ ($k_\theta \rho_{s,D} = 0.7$). The dominant instability transitions to the ITG when fast ions are considered, as they weaken the trapped-electron response and change the real frequency from positive to negative, thereby enhancing the relative stability of TEM and promoting the shift of ITG dominance to lower $k_\theta \rho_{s,H}$ and $k_\theta \rho_{s,D}$.

Moreover, the growth rate reaches its maximum value for all cases near $k_\theta \rho_s = 1.0$, where ITG modes are dominant. For $k_\theta \rho_{s,H} < 0.7$ ($k_\theta \rho_{s,D} < 0.7$), fast ions have little effect on TEM. However, in the region of $0.7 < k_\theta \rho_{s,H} < 1.65$ ($0.7 < k_\theta \rho_{s,D} < 1.72$), an obvious stabilizing effect on the dominant ITG mode is observed. This effect becomes more significant with increasing fraction of fast ions. The growth rate is reduced by approximately 10% when 10% fast ions are included, as shown in figure 6(b), where $\gamma_{ITG,max} =$

$1.15c_s/R_0$ with fast ions and $\gamma_{ITG,max} = 1.28c_s/R_0$ without fast ions. This stabilizing behavior can be attributed to the dilution effect, in which the introduction of fast ions reduces the relative density of main ions, thereby weakening the drive of the ITG mode. In summary, the ITG linear growth rate is found to decrease as the fast-ion fraction increases; notably, this stabilization is further enhanced by electron–electron collisions, as shown in figure 6(f).

3.3.2. Effect of temperature T_f Simulations are carried out with a fixed fast deuterium 10% fraction, setting $T_f = 10$ keV, 20 keV and 30 keV, respectively. The corresponding real frequency and growth rate are shown in figures 7(a)–(d), respectively.

The real frequency of the dominant instability decreases with increasing fast ion temperature. The transition of the dominant instability from TEM to ITG is consistently observed around $k_\theta \rho_{s,H} = 0.7$ ($k_\theta \rho_{s,D} = 0.7$), indicating that the temperature of fast ions has little influence on the transition of the dominant instability. Moreover, in the region of $k_\theta \rho_{s,H} < 0.7$ ($k_\theta \rho_{s,D} < 0.7$), the addition of fast ions with varying temperatures has little effects on the growth rate of the dominant TEM. In the range of $0.7 < k_\theta \rho_{s,H} < 1.65$ ($0.7 < k_\theta \rho_{s,D} < 1.72$), fast ions with temperatures of 20 keV and 30 keV produce similar stabilizing effects on the dominant ITG, both of which are more pronounced than that of 10 keV fast ions. The stabilizing effect changes little when $T_f > 20$ keV, and the dilution effect becomes dominant with high temperature of fast ions. In summary, the stabilizing effect of fast ions is found to be insensitive to the fast-ion temperature in the range of 10–30 keV (at a fixed 10% fraction). This suggests that the stabilization is dominated by dilution rather than kinetic resonance. Furthermore, figure 7(f) demonstrates that electron–electron collisions contribute an additional stabilizing effect.

3.3.3. Effect of temperature profile gradient

3.3.3.1. Effect of R/L_{T_i} Linear simulations are performed on the ion temperature gradient R/L_{T_i} for the mode with

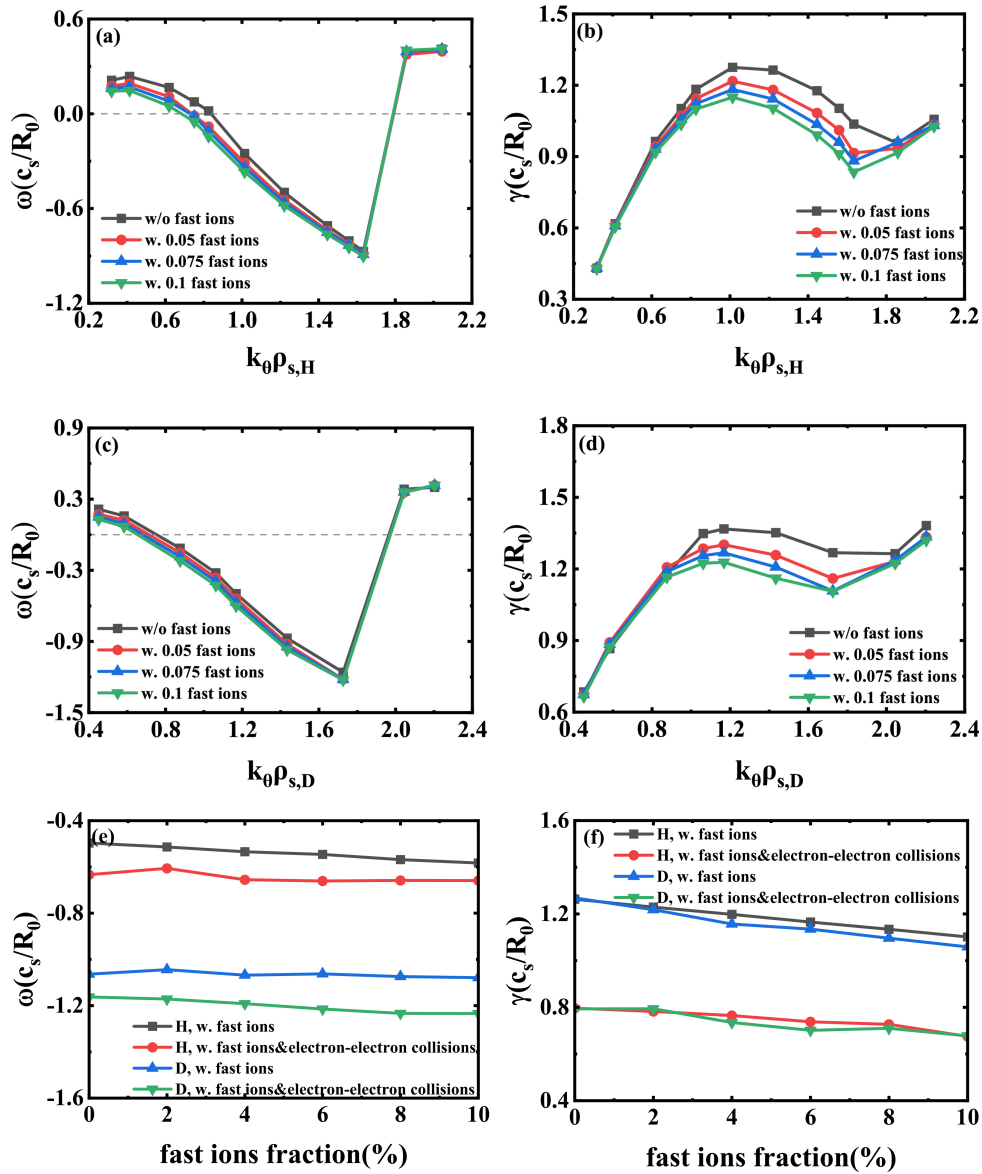


Figure 6. Effect of fast-ion fraction at $T_f = 20$ keV. (a) and (c) show the real frequency ω , while (b) and (d) display the growth rate γ for main ions of ((a), (b)) hydrogen and ((c), (d)) deuterium. The red, blue and green lines correspond to fast-ion fractions of 5%, 7.5% and 10%, respectively. (e) and (f) show ω and γ versus fraction of fast ions, respectively. The black line represents the case without fast ions.

$\gamma_{\text{ITG,max}}$ at $k_\theta \rho_s \approx 1$ from subsection 3.3.2, with fast deuterium ions at different temperatures of 10 keV, 20 keV and 30 keV, while maintaining a fixed 10% fraction. The real frequency and growth rate at different R/L_{T_i} are shown in figures 8(a)–(d), respectively.

The dominant instability transitions from TEM to ITG, as shown in figure 8. With the increase of R/L_{T_i} , ITG instability is excited. The R/L_{T_i} value at which the dominant instability shifts from TEM to ITG is reduced from approximately 15.8 (without fast ions) to 14.2 ($T_f = 30$ keV) and 12.4 ($T_f = 10$ keV), as shown in figure 8(a). The R/L_{T_i} value at which the dominant instability shifts from TEM to ITG is reduced from approximately 12.6 (without fast ions) to 12.2 ($T_f = 30$ keV) and 11.1 ($T_f = 10$ keV), as shown in figure 8(c), which indicates that the threshold R/L_{T_i} is decreased as the temperature of fast ions decreases. The R/L_{T_i} threshold for the transition of the dominant instability from TEM to

ITG is lower when the main ion is deuterium.

Moreover, the normalized growth rate decreases in the range of $1.5 < R/L_{T_i} < 12.4$, followed by a increase in the range of $14.2 < R/L_{T_i} < 20.7$ with increasing R/L_{T_i} . TEM is identified as the dominant instability within the range of $1.5 < R/L_{T_i} < 12.4$, whereas ITG dominates for $14.2 < R/L_{T_i} < 20.7$. R/L_{T_i} drives the ITG instability, resulting in an enhanced ITG growth rate but a suppressed TEM growth rate. Stabilization of ITG by fast ions with different temperatures is observed, the effects produced by 20 keV and 30 keV fast ions are more obvious than that of 10 keV. The stabilization effect is primarily ascribed to dilution. Growth rate of the dominant instability is larger when the main ion is deuterium than when the main ion is hydrogen.

3.3.3.2. Effect of R/L_{T_e} The influence of the electron temperature gradient R/L_{T_e} on the transition of dominant

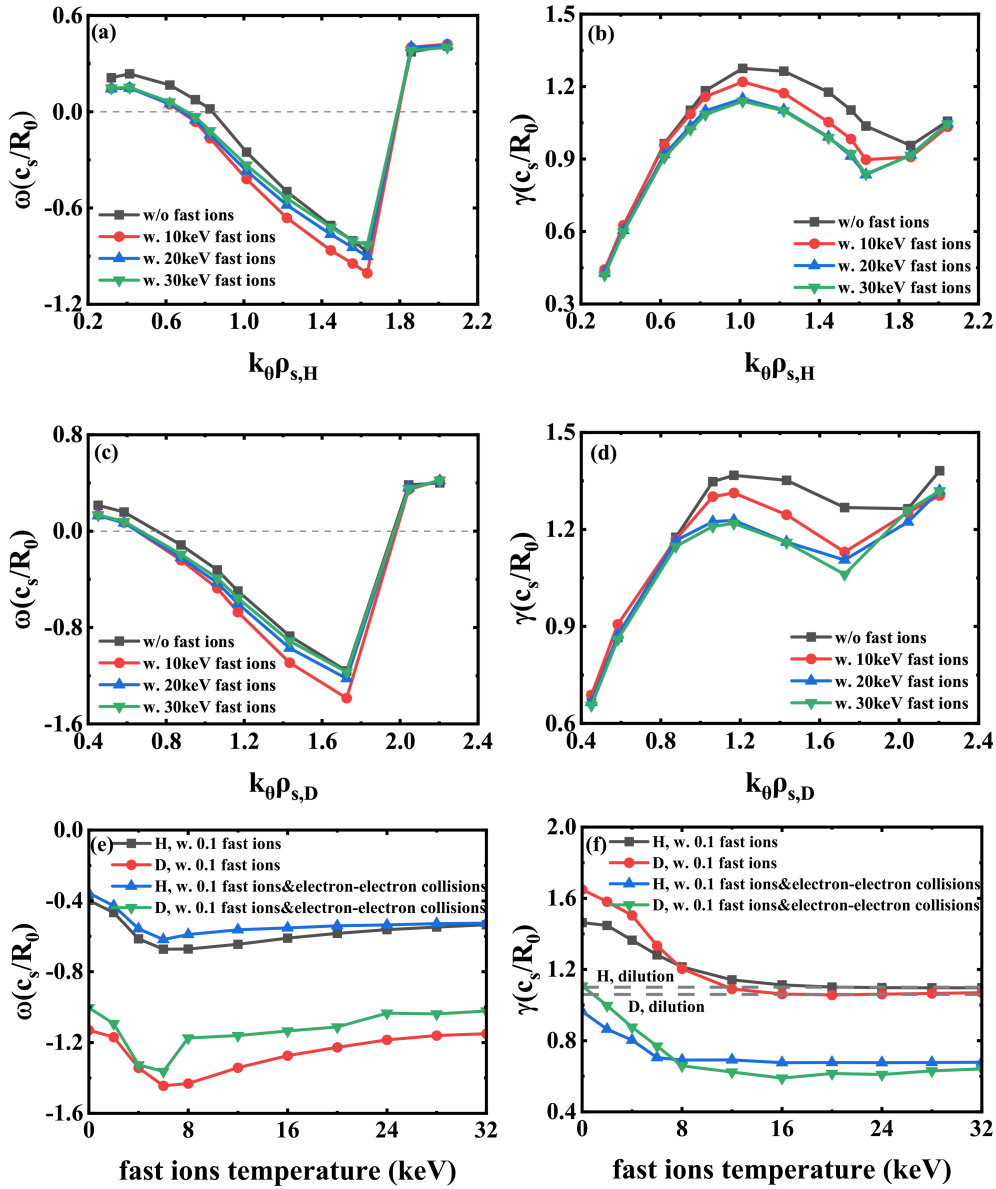


Figure 7. Effect of fast-ion temperature at 10% fraction. (a) and (c) show the real frequency ω , while (b) and (d) display the growth rate γ for main ions of ((a), (b)) hydrogen and ((c), (d)) deuterium. The red, blue and green lines correspond to fast-ion temperature of 10 keV, 20 keV and 30 keV, respectively. (e) and (f) show ω and γ versus temperature of fast ions, respectively. The black line represents the case without fast ions.

instability is also investigated. The real frequency ω and growth rate γ of the instabilities obtained from linear simulations are shown in figures 9(a)–(d), respectively.

The normalized real frequency increases with increasing R/L_{Te} , and the threshold of R/L_{Te} for the transition of the dominant instability from ITG to TEM decreases with increasing the temperature of fast ions. The transition thresholds are approximately 5.4 ($T_f = 10$ keV), 4.5 ($T_f = 20$ keV), and 4.1 ($T_f = 30$ keV) for R/L_{Te} , as shown in figure 9(a). The transition thresholds for R/L_{Te} are approximately 10.5 ($T_f = 10$ keV), 9.9 ($T_f = 20$ keV), and 9.5 ($T_f = 30$ keV), as shown in figure 9(c). The R/L_{Te} threshold for the transition of the dominant instability from ITG to TEM is lower when hydrogen is the main ion, indicating that this transition is easier in hydrogen plasmas.

Moreover, the normalized growth rate increases slowly

within the range of $1.3 < R/L_{Te} < 5.4$, and then increases rapidly for $5.4 < R/L_{Te} < 25.4$, as shown in figure 9(b). In figure 9(d), the normalized growth rate decreases slightly for $1.3 \leq R/L_{Te} \leq 6.5$ and then increases rapidly for $6.5 < R/L_{Te} < 25.4$. R/L_{Te} drives the TEM, enhancing its growth rate. Additionally, fast ions stabilize the ITG mode. Furthermore, the growth rate of TEM is higher when the main ion is deuterium than when the main ion is hydrogen. This observation is consistent with the conclusions from subsection 3.3.3.1.

To further investigate the threshold of the transition in dominant instability, the distribution of dominant modes in the parameter space of $R/L_{Te} = 4 - 28$ and $R/L_{Ti} = 4 - 18$ is presented in figure 10. In figure 10, the solid markers indicate the critical temperature gradient thresholds at which the dominant instability transitions between TEM and ITG under

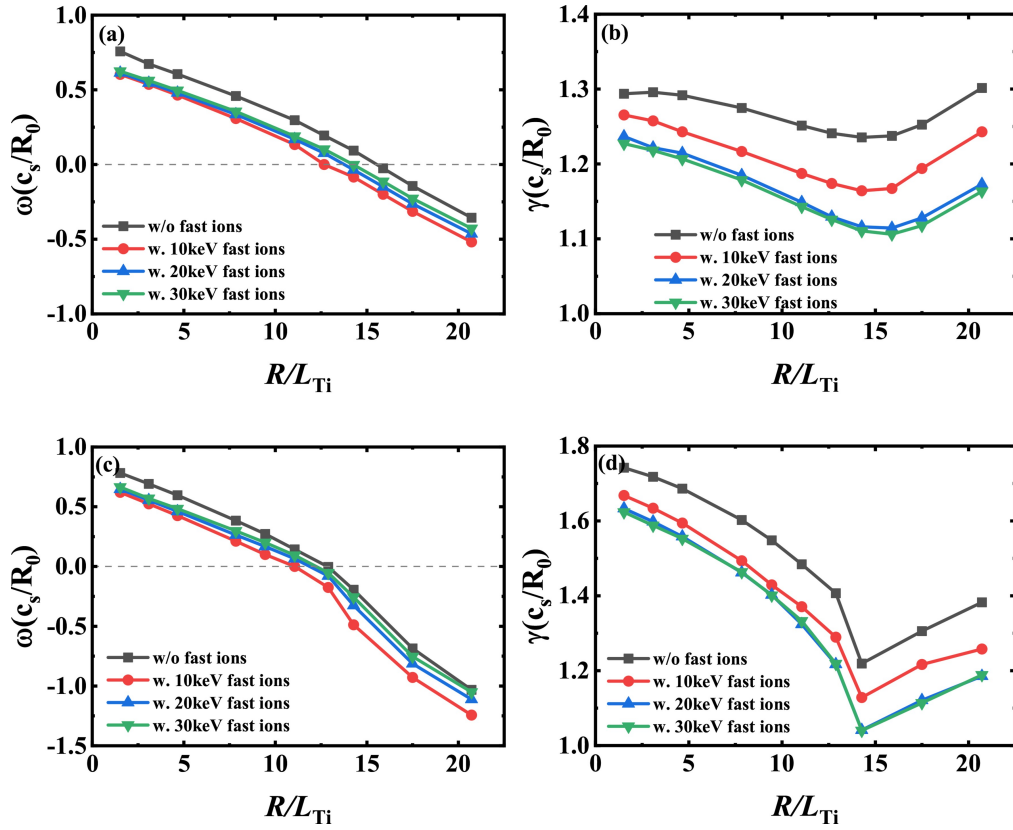


Figure 8. Effects of fast ions with $T_f = 10$ keV (red line), 20 keV (blue line) and 30 keV (green line) on ((a), (c)) the real frequency ω and ((b), (d)) growth rate γ are shown under different R/L_{Ti} conditions for main ions of ((a), (b)) hydrogen and ((c), (d)) deuterium, with $R/L_{Te} = 24.08$. The black line indicates the case without fast ions.

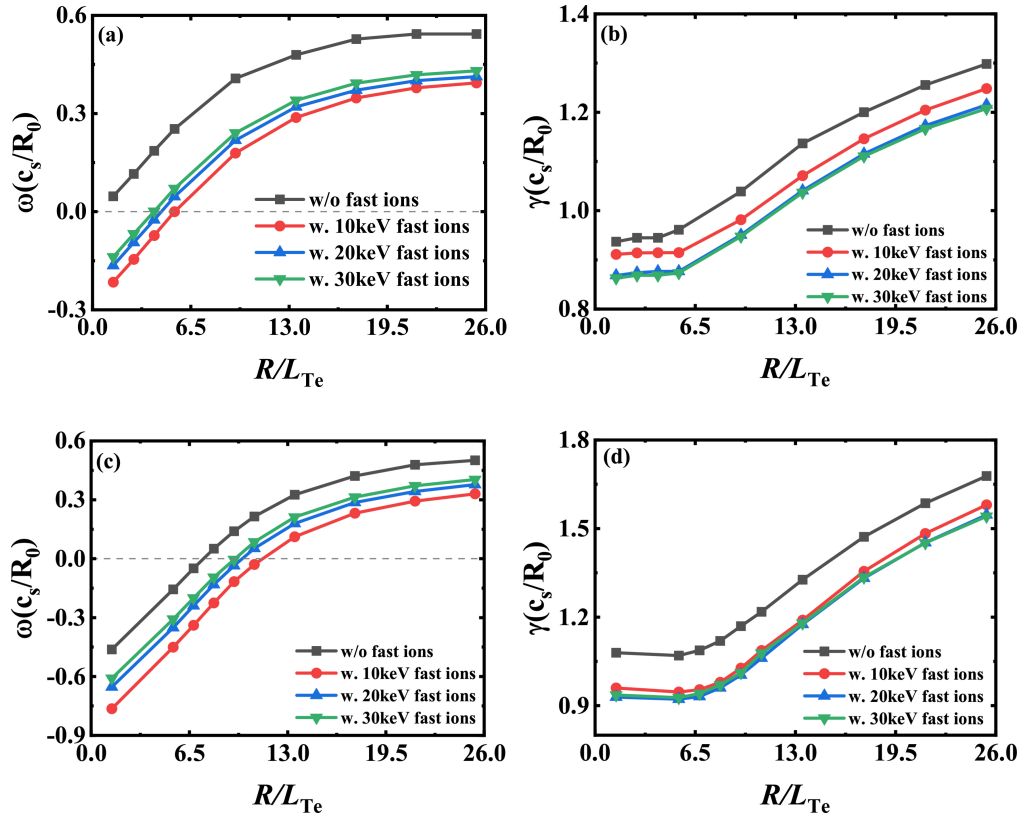


Figure 9. Effects of fast ions with $T_f = 10$ keV (red line), 20 keV (blue line), and 30 keV (green line) on ((a), (c)) the real frequency ω and ((b), (d)) growth rate γ are shown under different R/L_{Te} conditions for main ions of ((a), (b)) hydrogen and ((c), (d)) deuterium with $R/L_{Ti} = 6.25$. The black line represents the case without fast ions.

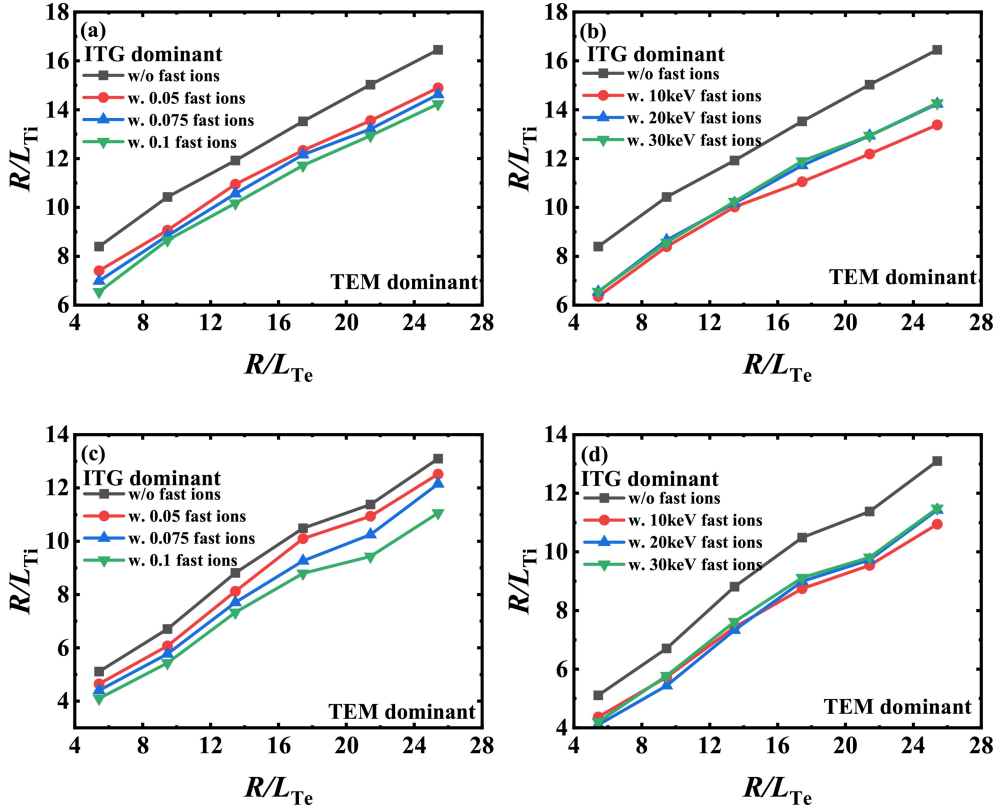


Figure 10. Threshold gradients between TEM and ITG modes in the $(R/L_{Te}, R/L_{Ti})$ plane. (a) and (c) show variations in fractions of fast ions (5%, 7.5% and 10%, indicated by red, blue and green lines), while (b) and (d) show variations in temperatures of fast ions (10 keV, 20 keV and 30 keV, also indicated by red, blue and green lines) for main ions of ((a), (b)) hydrogen and ((c), (d)) deuterium. The black line represents the case without fast ions.

different fractions or temperatures of fast ions. During the linear simulations, modes with frequencies satisfying $\omega \leq 10^{-3} (c_s/R_0)$ are treated as “zero-frequency modes”. The region above the boundary lines in figure 10 corresponds to the ITG dominated regime with $\omega < 0$, while the region below corresponds to the TEM dominated regime with $\omega > 0$.

As shown in figure 10, when R/L_{Te} (or R/L_{Ti}) is fixed, increasing R/L_{Ti} (or R/L_{Te}) leads to a transition of the dominant instability from TEM to ITG (or from ITG to TEM). The threshold of R/L_{Ti} for the transition of the dominant instability from TEM to ITG is reduced, and it decreases further with increasing fraction of fast ions, when fast ions are taken into account. In figure 10(a), at $R/L_{Te} = 5.43$, the threshold values of R/L_{Ti} are 8.40 ($n_f/n_e = 0$), 7.41 ($n_f/n_e = 0.05$), 6.99 ($n_f/n_e = 0.075$), and 6.54 ($n_f/n_e = 0.1$). Fast ions weaken the trapped-electron response, reducing the trapped-electron drive so that the dominant mode switches from TEM to ITG, thereby lowering the R/L_{Ti} threshold in figure 10.

Moreover, fast ions with lower temperature (10 keV) reduce the transition threshold of R/L_{Ti} more significantly than those with higher temperatures (20 keV and 30 keV). This can be attributed to the resonance between fast ions and ITG modes, which becomes weaker with increasing T_i/T_e . Lower T_i enhances resonance and reduces the threshold for ITG dominance. On the other hand, the temperature gradient of fast ions is relatively steep ($R/L_{Ti} = R/L_{Te} = 24.08$), which further enhances the resonance between fast ions and

ITG modes, increases the real frequency of the ITG mode, and consequently lowers the R/L_{Ti} threshold required for the dominance of ITG modes.

3.3.4. Effect of collisionality The effects of electron-electron collisions on the dominant instability are investigated. The real frequency and growth rate versus $k_{\theta}\rho_s$ are shown in figures 11(a)–(d), respectively. Simulations including ion-ion collisions are also performed. The results show that ion-ion collisions have little effects on the dominant instability. Therefore, the corresponding results are not shown.

TEM are replaced by ITG in the range of $0.4 \leq k_{\theta}\rho_{s,H} \leq 0.8$ ($0.4 \leq k_{\theta}\rho_{s,D} \leq 0.8$) and $k_{\theta}\rho_{s,H} \geq 1.85$ ($k_{\theta}\rho_{s,D} \geq 2.04$) when electron-electron collisions are included, as shown in figure 11. In contrast, within the range of $0.8 \leq k_{\theta}\rho_{s,H} \leq 1.6$ ($0.8 \leq k_{\theta}\rho_{s,D} \leq 1.7$), the ITG related real frequencies remain relatively unchanged. Moreover, electron-electron collisions significantly stabilize the mode, reducing the growth rate by approximately 50%.

The growth rate is significantly higher compared to the cases when electron-electron collisions are included. This discrepancy is attributed to the destabilizing effect of trapped electron dynamics on ITG modes. To further investigate this mechanism, kinetic electrons are replaced by adiabatic electrons (blue line in figure 11). The real frequencies and growth rates closely resemble those obtained in the kinetic model with electron-electron collisions, indicating that the

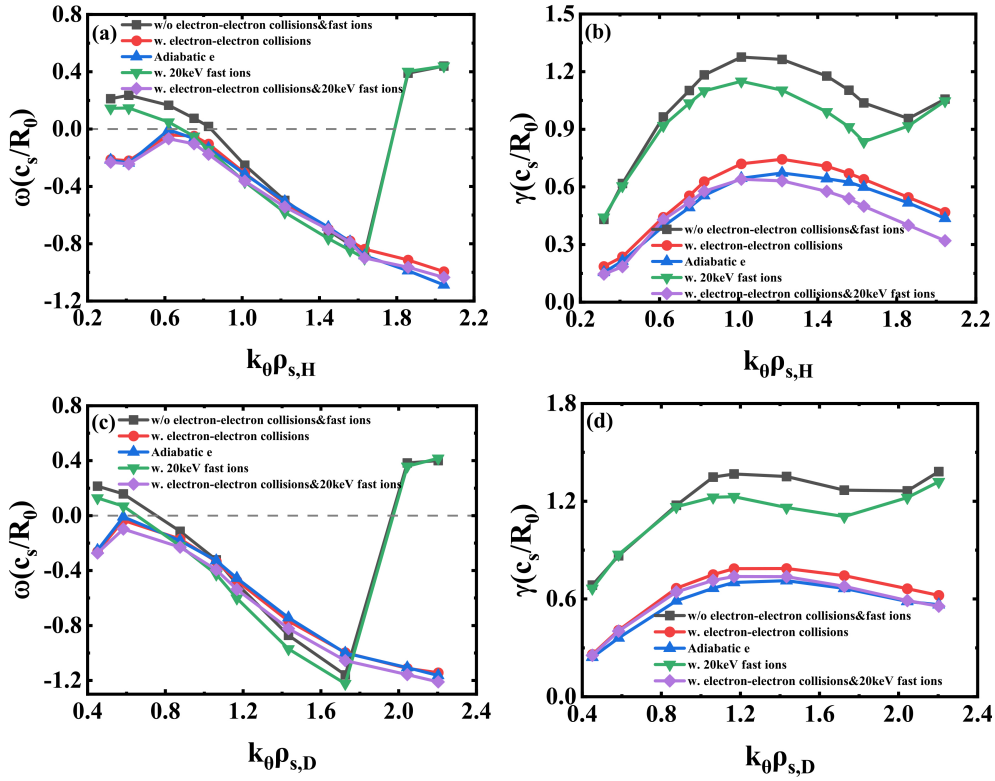


Figure 11. Effects of electron-electron collision (red and purple lines) on ((a), (c)) the real frequency ω and ((b), (d)) growth rate γ for main ions of ((a), (b)) hydrogen and ((c), (d)) deuterium. The black line represents the case without fast ions and collision effect, while the green line represents the case with fast deuterium ions with 20 keV and 10% fraction of fast ions.

inclusion of electron–electron collisions suppresses the response of trapped electrons. Consequently, the ITG growth rate is reduced by nearly 50%, indicating the essential role of electron–electron collisions in stabilizing ITG dominated modes.

4. Discussion and conclusion

Linear simulations are performed using the GTC code to investigate the dominant microinstabilities in EAST, with mainly on the influence of fast ions and collision on the transition of the dominant instability between TEM and ITG.

Simulations are performed with hydrogen or deuterium as the main ion, with 5%, 7.5% and 10% fast ions, and 10 keV, 20 keV and 30 keV fast ions. The results indicate that fast ions destabilize the ∇n_e -TEM but stabilize the ∇T_e -TEM, and also significantly stabilize the ITG mode. The effect becomes increasingly obvious with higher fractions and temperatures of fast ions, reaching its maximum stabilizing effect of approximately 10% when the fraction of fast ions is 10% and temperature is 30 keV. Dilution effects are primarily responsible for the stabilization when $T_f \geq 10$ keV. The transition of the dominant instability from TEM to ITG is found at lower $k_0 \rho_s$ ($k_0 \rho_s \approx 0.7$) when fast ions are considered. Parametric analyses of R/L_{T_i} and R/L_{T_e} further demonstrate that the introduction of fast ions lowers the R/L_{T_i} values required for the transition of the dominant instability. For the considered parameters ($T_e = 2.51$ keV, $R/L_{T_e} =$

24.08, $R/L_{n_e} = 6.8$, $n_f/n_e \leq 0.10$, $T_f = 10$ –30 keV), the R/L_{T_i} threshold for the transition of the dominant instability is valid, but it shifts with changes in R/L_{T_e} , n_f/n_e , or other parameters. The threshold R/L_{T_i} decreases to 14.2 ($T_f = 30$ keV) and 12.4 ($T_f = 10$ keV) for hydrogen plasmas, compared with the R/L_{T_i} value without fast ions ($R/L_{T_i} = 15.8$), and it decreases to 12.2 ($T_f = 30$ keV) and 11.1 ($T_f = 10$ keV) for deuterium plasmas, compared with the R/L_{T_i} value without fast ions ($R/L_{T_i} = 12.6$). The R/L_{T_i} of the transition of the dominant instability increases with increasing temperature of fast ions. The R/L_{T_i} of the transition of the dominant instability decreases when fast ions are considered, and the decrease is more significant for deuterium plasmas. Furthermore, the normalized real frequency increases with increasing R/L_{T_e} , and the threshold of R/L_{T_e} for the transition of the dominant instability from ITG to TEM decreases with increasing temperature of fast ions. The transition thresholds are approximately 5.4 ($T_f = 10$ keV), 4.5 ($T_f = 20$ keV) and 4.1 ($T_f = 30$ keV) for hydrogen plasmas, while the corresponding thresholds are about 10.5, 9.9 and 9.5 for deuterium plasmas. The R/L_{T_e} for the transition of the dominant instability is lower when hydrogen is the main ion.

Electron–electron collisions significantly reduce the TEM growth rate to approximately 70% of the collisionless value, indicating their stabilizing effect on TEM dominated instabilities under typical EAST plasma parameters. Electron–electron collisions suppress trapped electron resonance and reduce the ITG growth rate by nearly 50%. In particular,

the transition of the dominant instability is observed for low- $k_{\theta}\rho_s$ ($0.4 \leq k_{\theta}\rho_{s,H} \leq 0.8$, $0.4 \leq k_{\theta}\rho_{s,D} \leq 0.8$) modes when electron–electron collisions are taken into account. The effect of ion–ion collisions on the real frequency and growth rate of both TEM and ITG dominated modes is negligible. The reason is that the ion–ion collision frequency is much lower than the real frequency of the dominant instability. In contrast, the frequency of electron–electron collisions in the simulation is of the same order as the real frequency of the dominant instability, thereby reducing the resonant response of trapped electrons and significantly stabilizing the mode. The linear simulation results show that fast ions reduce the linear growth rate of the dominant instabilities, suggesting a corresponding reduction in turbulent transport in future nonlinear regimes, potentially through zonal-flow regulation and nonlinear mode coupling. Typical EAST parameters are employed to interpret EAST experiments. The impact of density gradients of fast ions on the transition will be investigated in future work.

Acknowledgments

This work was supported by National Natural Science Foundation of China (No. 12375215), the National MCF Energy R&D Program of China (No. 2019YFE03060000).

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