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Gyrokinetic simulation of electromagnetic instabilities in the high β_p scenario on EAST

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Abstract

High poloidal beta scenarios with favorable plasma performance ($\beta_p \sim 2.0$, $H_{98} \sim 1.3$) have been achieved on Experimental Advanced Superconducting Tokamak (EAST) since the 2018 international atomic energy agency (IAEA). Linear electromagnetic gyrokinetic simulations using gyrokinetic toroidal code (GTC) code are performed based on the experimental data of a typical high β_p discharge on EAST. In the core region of plasma, an electromagnetic instability with similar β_e dependence and mode structure with kinetic ballooning mode (KBM) but exhibits positive or nearly zero frequency is observed. This instability is referred as unconventional KBM (UKBM). Simulation results demonstrate that UKBM occurs in low ion–electron temperature ratio conditions and UKBM will transit to KBM when ion–electron temperature is high. Further investigation shows the driven mechanism of UKBM differs at different electron beta region. When the electron beta exceeds the threshold of electrostatic instability to UKBM, UKBM is driven by electron pressure gradient. When electron beta is close to the beta threshold of UKBM, the main driven mechanism is η_e . Reversed magnetic shear is found to have a significant stabilize effect on UKBM.

Keywords: high poloidal beta, gyrokinetic simulation, electromagnetic instability

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

1. Introduction

The major goal of Experimental Advanced Superconducting Tokamak (EAST) is to achieve stable long-pulse, high performance, fully non-inductive plasma operation. The high β_p scenario has been one of the main research interests of EAST experiments since the accompanying high bootstrap current fraction, which is essential for steady-state long-pulse discharge [1, 2]. Here, β_p is defined as the ratio

of plasma pressure to the poloidal magnetic field pressure, $\beta_p = P / (B_p^2 / 2\mu_0)$, where P is the plasma pressure and B_p is the poloidal magnetic field. High β_p scenarios sustained by pure RF heating or together with neutral beam Injection (NBI) heating have been successfully established on EAST and reaches quite well energy confinement ($\beta_p \sim 2 - 2.5$, $H_{98} \sim 1.1 - 1.3$) [3–5]. Integrated modeling performed against a high β_p discharge on EAST shows quite well agreement with experimental measurements in both temperature and density profiles [6]. The modeling results indicate that the confinement improvement in these high β_p discharges are attributed to the

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reduction of turbulent transport by collisional stabilization in trapped electron mode (TEM). A similar modeling using transport code trapped gyro landau fluid code (TGLF)

against another high β_p discharge using only RF heating also shows the dominant instability in core of plasma is TEM [7]. By utilizing the gyrokinetic simulation method based on first principle, our previous work also prove that the dominant instability in core of high β_p discharge plasma is TEM [8]. Those previous works [6–8] mainly focus on the electrostatic instabilities in the high β_p discharges on EAST. To fulfill the realistic physics, the electromagnetic effects should be considered under high β_e conditions. Here, $\beta_e = 8\pi T_e n_e / B^2$ is the electron > beta.

It is well known that the electrostatic ion temperature gradient (ITG) mode is stabilized by the electromagnetic effects [9, 10]. The growth rate of TEM remains unchanged with increasing β_e while the electromagnetic kinetic ballooning mode (KBM) becomes unstable when β_e exceeds a critical, the growth rate of KBM keeps increasing until β_e reaches the second stability region [11, 12]. Previous research on KBM mainly focus on those situations with $T_i \geq T_e$. For Cyclone base case ($T_i = T_e$) [13], KBM dominate over TEM at $\rho = 0.5$ when $\beta_e > 1.5\%$ and the frequency exhibits a jump from positive value to negative value [14], which indicates that KBM propagates in the ion diamagnetic direction. KBM is partly stabilized by strong magnetic shear and sensitive to temperature gradient rather than density gradient [15]. For core plasma in the high β hybrid discharge on joint european torus (JET) ($T_i \approx 1.5 \times T_e$), gyrokinetic simulation results show that the dominant instability at $\rho = 0.15$ is KBM and fast ion effects reduces the growth rate of KBM [16]. For high β_p cases on EAST, the core electron temperature is often much higher than the ion temperature ($T_e > 5 \times T_i$), the properties of KBM or other electromagnetic instabilities should be further recovered in this situation.

In this work, the electromagnetic instabilities in a high β_p discharge on EAST is studied by gyrokinetic simulations. The rest parts of this paper is organized as follows. Section 2 gives the experimental parameters and the simulation setups. The gyrokinetic code gyrokinetic toroidal code (GTC) that we used in this work is also introduced briefly. The simulation results are presented in section 3 and the conclusions and discussions are given in section 4.

2. Experimental and simulation setup

2.1. Experimental setups

Since the 2018 IAEA, EAST experiments have successfully demonstrated the high β_p scenario with higher plasma performance [17]. Time evolution of main parameters of a typical discharge (shot 90949) with a duration over 60 s are shown in figure 1. The plasma current I_p is about 0.35 MA and the plasma is fully non-inductive driven after 3 s (loop voltage $V_{loop} \sim 0$). Other parameters are: $\beta_p \sim 2.0$, $\beta_N \sim 1.6$, $H_{98y2} \sim 1.3$, line-averaged electron density $n_e \sim 3.5 \times 10^{19} \text{ m}^{-3}$. The heating methods include 2.5 MW lower hybrid wave (LHW) and 0.9 MW electron cyclotron resonance heating (ECRH).

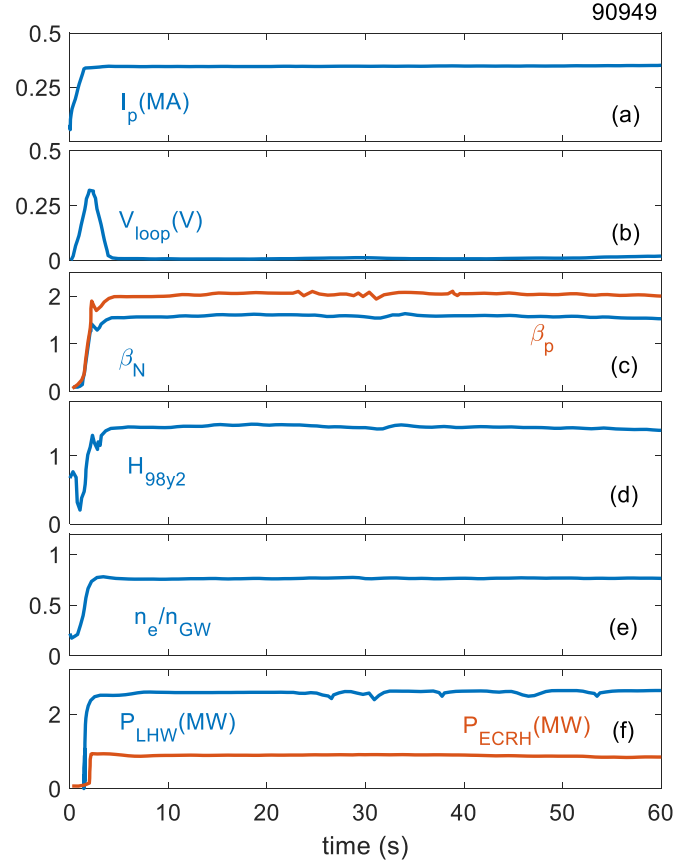


Figure 1. Time history of shot 90949 on EAST: (a) plasma current, (b) loop voltage, (c) poloidal beta and normalized beta, (d) H_{98y2} energy confinement factor, (e) line-average electron density over Greenwald density limit, (f) auxiliary heating powers of LHW and ECRH.

The following gyrokinetic simulations are performed using experimental data of shot 90949 at 20 s when the plasma parameters are stable. The experimental plasma profiles and the corresponding scale length are shown in figure 2. Here, η_α is defined as $\frac{R/L_{T\alpha}}{R/L_{n\alpha}}$ where α is ion and electron. The electron temperature (T_e) profile is obtained by Thomson scattering (TS) diagnostics [18], the ion temperature (T_i) is measured by charge exchange recombination spectroscopy plus x-ray crystal spectrometer [19] and the electron density (n_e) is reconstructed from polarimeter-interferometer (POINT) [20] along with TS diagnostics. The electron and ion temperature on axis are 5.5 keV and 1.0 keV, respectively. The peak T_e profile with internal transport barrier (ITB) and flat T_i profile and high T_e/T_i are typical features of high β_p discharges using only radio frequency (RF) heating on EAST [5, 17]. The electron temperature scale length (R/L_{Te}) is also much higher than ion temperature scale length (R/L_{Ti}) and electron density scale length (R/L_{ne}) at most radial positions. To investigate the instabilities under different plasma parameters region, linear gyrokinetic simulations are performed focusing on two radial positions: $\rho = 0.24$ and $\rho = 0.48$, where ρ is the normalized minor radius. R/L_{Te} reaches maximum value at $\rho = 0.24$, R/L_{Ti} reaches a peak and $R/L_{Ti} \approx R/L_{ne}$ at $\rho = 0.48$. Main

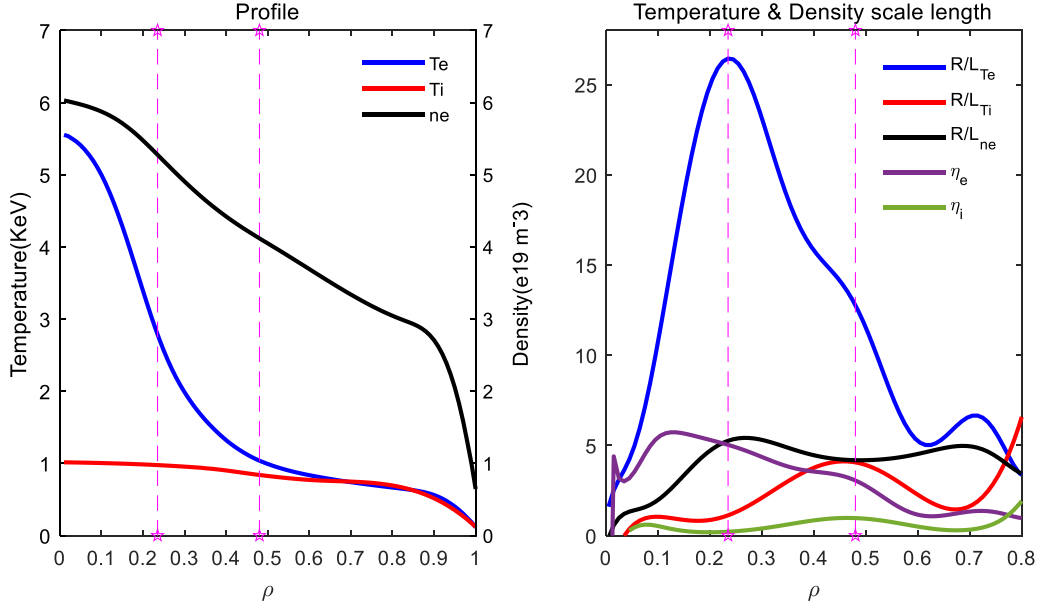


Figure 2. Radial profiles of electron temperature, electron density, ion temperature and the corresponding scale length of shot 90949.

Table 1. Main plasma parameters of shot 90949 at 20 s at $\rho = 0.24$ and $\rho = 0.48$.

ρ	T_e (keV)	T_i (keV)	n_e (10^{19} m^{-3})	$\frac{R}{L_{Te}}$	$\frac{R}{L_{Ti}}$	$\frac{R}{L_{ne}}$	q	s	β_e (%)
0.24	2.79	0.98	5.28	26.44	1.12	5.26	1.10	0.21	1.42
0.48	1.04	0.84	4.12	12.76	4.06	4.18	1.60	0.86	0.29

plasma parameters at these two radial position at 20 s are given in table 1.

2.2. Simulation model and setups

Gyrokinetic simulation code GTC utilized in this work is a global simulation code using particle in cell method with electromagnetic capability. GTC solves the Vlasov equation which is written as

$$\frac{d}{dt}f_\alpha(\mathbf{X}, \mu, v_\parallel, t) = \left[\frac{\partial}{\partial t} + \dot{\mathbf{X}} \cdot \nabla + v_\parallel \frac{\partial}{\partial v_\parallel} \right] f_\alpha = 0, \quad (1)$$

where f_α is the distribution function, $\mathbf{X}$ is the gyrocenter position, μ is the magnetic moment, and $v_\parallel$ is the parallel velocity. The subscript denotes the particle species. The time deviation of X and $v_\parallel$ are written as

$$\dot{\mathbf{X}} = v_\parallel \frac{\mathbf{B}}{B_0} + \mathbf{v}_E + \mathbf{v}_d + \mathbf{v}_{b\parallel}, \quad (2)$$

$$\dot{v}_\parallel = -\frac{1}{m_\alpha} \frac{\mathbf{B}^*}{B_0} \cdot (\mu \nabla B_0 + Z_\alpha \nabla \langle \phi \rangle) - \frac{Z_\alpha}{m_\alpha c} \frac{\mathbf{B}^*}{B_0} \cdot \nabla \delta A_\perp \cdot v_\perp - \frac{Z_\alpha}{m_\alpha c} \frac{\partial \delta A_\parallel}{\partial t}, \quad (3)$$

where $\mathbf{B} \equiv \mathbf{B}_0 + \delta \mathbf{B}_\perp$, $\mathbf{B}_0$ and $\delta \mathbf{B}$ are equilibrium and perturbed magnetic field, respectively. $\mathbf{B}^* = \mathbf{B}_0^* + \delta \mathbf{B}_\perp^*$ is the modified magnetic field with $\mathbf{B}_0^* = \mathbf{B}_0 + \frac{B_0 v_\parallel}{\Omega_\alpha} \nabla \times \mathbf{b}_0$, in which Ω_α is the gyro-frequency. $\mathbf{v}_E$ and $\mathbf{v}_d$ are $\mathbf{E} \times \mathbf{B}$ drift velocity

and magnetic drift velocity. $\mathbf{v}_{b\parallel}$ is the gradient drift caused by the perturbed parallel magnetic field. m_α and Z_α denote the mass, charge of particle. $\langle \dots \rangle$ is the gyro-orbit averaging.

The perturbed electrostatic potential ϕ , parallel vector potential $A_\parallel$ and parallel part of perturbed magnetic field $B_\parallel$ are calculated using gyrokinetic Poisson's equation, parallel Ampere's law and perpendicular Ampere's law, respectively. These equations are written as

$$\frac{4\pi Z_i^2 n_i}{T_i} (\phi - \tilde{\phi}) = 4\pi (Z_i n_i - e n_e), \quad (4)$$

$$\nabla_\perp^2 A_\parallel = \frac{4\pi}{c} (e n_e u_{pe} - Z_i n_i u_{pi}). \quad (5)$$

$$\nabla_\perp B_\parallel \times \mathbf{b}_0 = \frac{4\pi}{c} (Z_i n_i u_{\perp i} - e n_e u_{\perp e}) \quad (6)$$

where $\tilde{\phi}$ is the gyro-phase averaged potential. The density n_α and velocity $n_\alpha u_\alpha$ are obtained by the fluid moments of the corresponding distribution functions. Furthermore, a perturbative δf simulation method and a fluid-kinetic hybrid electron model are implemented in GTC to improve the computational efficiency. The detailed function utilized in GTC are shown in [21, 22].

Benchmarks among GTC and other gyrokinetic simulation codes on electrostatic (ITG and TEM) and electromagnetic (KBM) instabilities have been carried out to evaluate the accuracy of this code, and the results agree well with that of other codes [14, 23–25]. Part of the simulation setups

are set as follows after performing a series of convergence tests. To improve the computational efficiency, the simulation region is between $\rho = 0.1 - 0.3$ and $\rho = 0.4 - 0.6$ when we focus on $\rho = 0.24$ and $\rho = 0.48$, respectively. Fixed boundary conditions are applied at both sides of radial domain and periodic boundary conditions are applied in poloidal and toroidal direction. The major radius $R_0 = 1.9$ m, the minor radius $a = 0.4$ m, the toroidal magnetic field $B_T = 2.38$ T, simulation time step $t_{\text{step}} = 0.002R_0/c_s$, where c_s is the ion acoustic velocity. The radial and poloidal length of grids are about $0.75 \times \rho_i$, where ρ_i is the ion Larmor radius. The main ion is deuterium ($m_D/m_e = 3672$).

3. Simulation results and discussion

3.1. $k_\theta \rho_s$ scan

The ion-scale linear electromagnetic simulations are performed and the turbulence spectrums at two radial positions are shown in figure 3. The growth rate peaks at $k_\theta \rho_s = 0.629$ and 0.450 at $\rho = 0.24$ and 0.48 , respectively. Here k_θ is poloidal wave vector and $\rho_s = \sqrt{T_e m_i / e B_0}$ is the ion-sound Larmor radius. It can be also seen that the growth rate at $\rho = 0.24$ is higher than that at $\rho = 0.48$, this could be explained by the high electron temperature gradient at $\rho = 0.24$. In nonlinear simulations, the toroidal mode number of the dominant instability is usually lower compared to that in the linear simulations [26, 27]. So instabilities for two different $k_\theta \rho_s$ are chosen to perform parameters' scan for each radial position. Specifically, $k_\theta \rho_s = 0.314, 0.629$ for $\rho = 0.24$ and $k_\theta \rho_s = 0.321, 0.450$ for $\rho = 0.48$.

At $\rho = 0.24$, the real frequency (ω) of instabilities for $k_\theta \rho_s \geq 0.629$ are positive, which denote that the modes propagate in the electron diamagnetic direction. However, the ω of instabilities for $k_\theta \rho_s < 0.629$ is close to zero. These fluid-like pure growing modes are unlike that discovered in previous research, which occurs in the transition region of ubiquitous mode and TEM in a narrow range of $k_\theta \rho_s$ [28]. Similar situation is observed at $\rho = 0.48$, ω is close to zero for $0.257 < k_\theta \rho_s < 0.643$ and ω is positive in other region. In section 3.3, we will show that these zero and positive frequencies are due to the high electron-ion temperature ratio (T_e/T_i) in this high β_p discharge.

3.2. β_e scan

The electromagnetic effects are investigated by varying electron density ($\beta_e = 8\pi T_e n_e / B^2$) and the results are given in figures 4 and 6. At $\rho = 0.24$, the growth rate for $k_\theta \rho_s = 0.314$ and 0.629 show similar trend. By remaining the nonadiabatic part of the electron distribution function in the fluid-kinetic hybrid electron model of GTC [29], the simulation results show that γ is insensitive to β_e when $\beta_e < 0.8\%$. Electrostatic simulation is also performed and the growth rate is nearly the same as that obtained by electromagnetic simulations when $\beta_e < 0.8\%$, which indicates that the electromagnetic

(EM) effects are not important at these cases. On the other hand, the γ obtained by simulation using adiabatic electron model grows monotonically with β_e . When $\beta_e < 0.8\%$, the growth rate obtained by simulation using adiabatic electron model is lower than that obtained by simulation using non-adiabatic electron model, which denotes that trapped electron effects play an important role in these modes. These results indicate that the dominant instability is electrostatic TEM when $\beta_e < 0.8\%$. When $\beta_e > 0.8\%$, simulation using adiabatic electron model and nonadiabatic electron model both show that the γ increase with increasing β_e . The γ obtained by simulation using adiabatic electron model is slightly higher than that of simulation using nonadiabatic electron model. These properties are similar to that of KBM. However, unlike the conventional KBM which exhibits negative frequency, these modes here show near zero or positive frequencies. It can be also seen that the electromagnetic mode at $\rho = 0.24$ with nearly zero frequency ($k_\theta \rho_s = 0.314$) shows similar β_e dependence with the mode with positive frequency ($k_\theta \rho_s = 0.629$).

The mode structure of the instability at $\rho = 0.24$ is shown in figure 5. Typical ballooning mode structure of drift turbulence in tokamak geometry is observed. The perturbed electrostatic potential is stronger at $\theta \approx 0$, the perturbed parallel vector potential peaks at $\theta \approx \pm \frac{\pi}{2}$ and the amplitude of $v_A A_{\parallel}$ is close to that of ϕ , where $v_A = B_0 / \sqrt{4\pi n_e m_i}$. Therefore, we recognize the dominant instability at $\rho = 0.24$ is a kind of electromagnetic instability with similar β_e dependence but different frequency compared with conventional KBM.

β_e scan at $\rho = 0.48$ is shown in figure 6. The growth rate obtained by electromagnetic simulation using experimental value of β_e is close to the γ obtained by electrostatic simulation. It can be also seen that the growth rate increases with increasing β_e after β_e exceeds 0.4% , which means the experimental β_e is close to the critical value that electrostatic instability transit to electromagnetic instability. The mode structure at this case is shown in figure 7. The perturbed electrostatic potential is also higher at the outer region but the amplitude of $v_A A_{\parallel}$ is much lower than that of ϕ . This demonstrates that the electromagnetic part of the instability is weaker compared to situation at $\rho = 0.24$. Though the γ obtained by electromagnetic simulation using experimental β_e is close to that of electrostatic simulation, the electromagnetic effects do have influence on the frequency. As mentioned in section 3.1, the ω calculated by GTC code when using experimental β_e is close to zero and the ω keeps around zero when β_e increases. In summary, the β_e at $\rho = 0.48$ is close to the beta threshold of transition between electrostatic instabilities and electromagnetic instabilities. This results in electromagnetic effects having little effect on the growth rate but significant effect on the frequency. The dominant instability here exhibits a growth rate similar to electrostatic TEM and a frequency close to zero, which is the property of the electromagnetic instability at $\rho = 0.24$.

By comparing figures 4 and 6, it can be seen that the β_e threshold of the electromagnetic instability is different

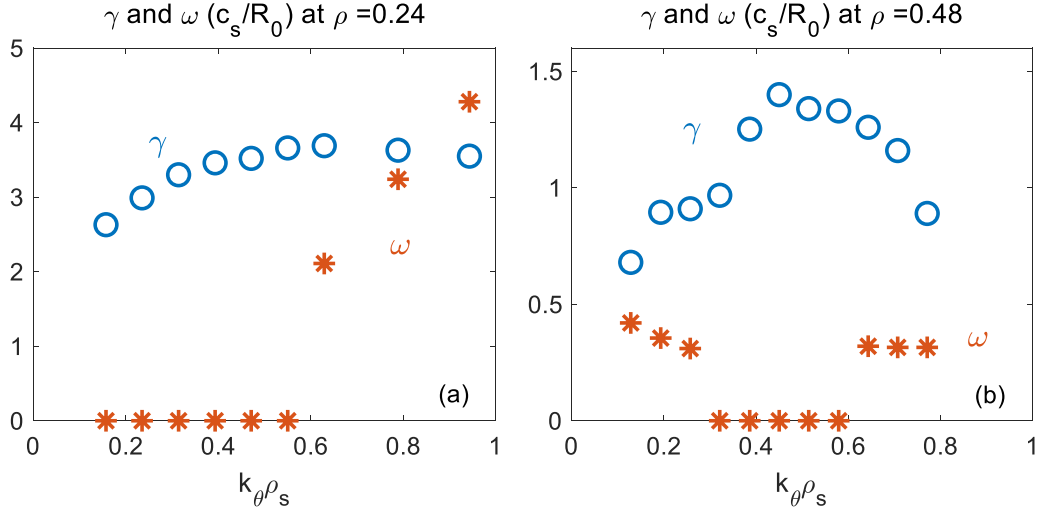


Figure 3. Turbulence linear growth rate and frequency spectrum for different $k_\theta \rho_s$ at $\rho = 0.24$ (a) and $\rho = 0.48$ (b) at 20 s of shot 90949.

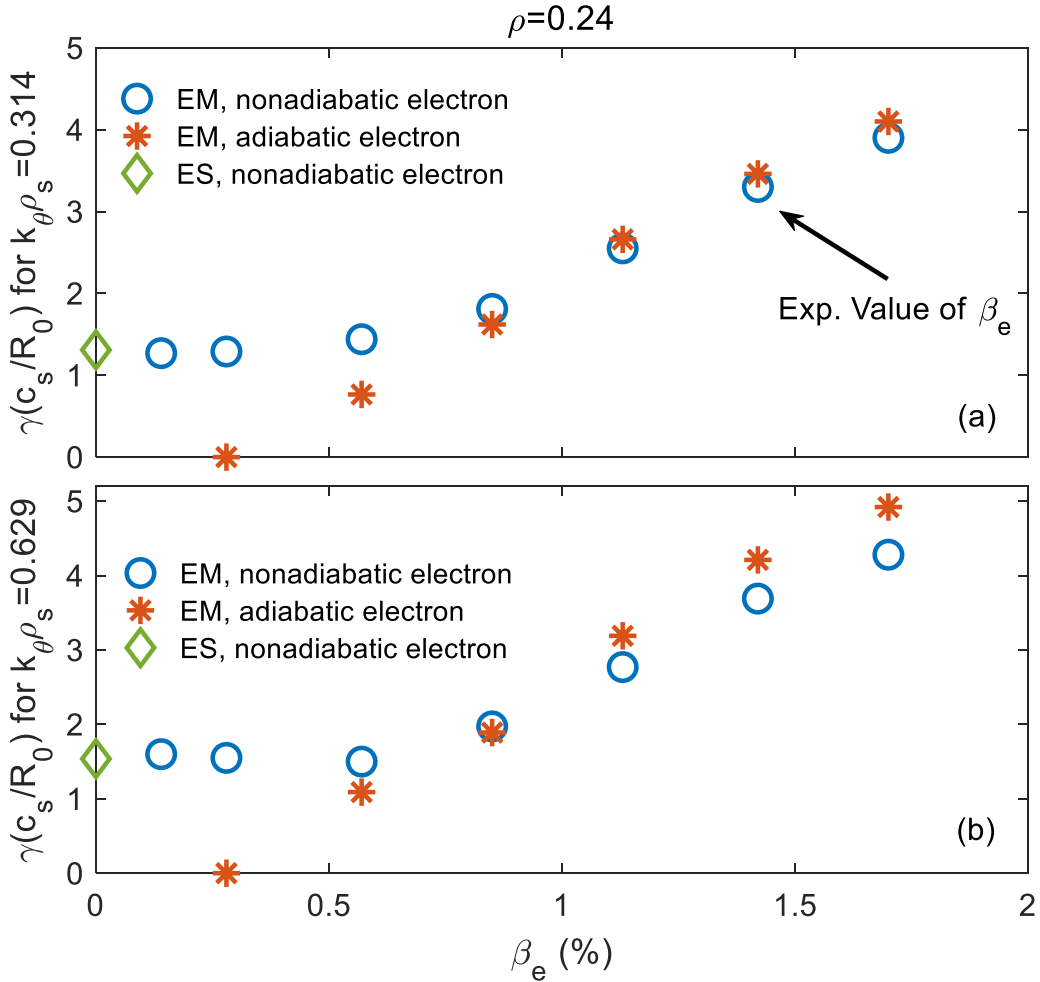


Figure 4. β_e dependence of the linear growth rate for $k_\theta \rho_s = 0.314$ (a) and $k_\theta \rho_s = 0.629$ (b) at $\rho = 0.24$ at 20 s of shot 90949.

in different radial positions ($\sim 0.8\%$ at $\rho = 0.24$ and $\sim 0.4\%$ at $\rho = 0.48$). The β_e threshold of KBM in CBC case is about 1.5% [14]. These indicate that the β_e threshold of the electromagnetic is relative to the local parameters of the plasma, such as the temperature and density gradient and magnetic shear.

3.3. T_i/T_e scan

As mentioned in the previous sections, the dominant instability at $\rho = 0.24$ of the high β_p discharge on EAST is a kind of electromagnetic instability which exhibits the similar β_e dependence with the conventional KBM, but the frequency

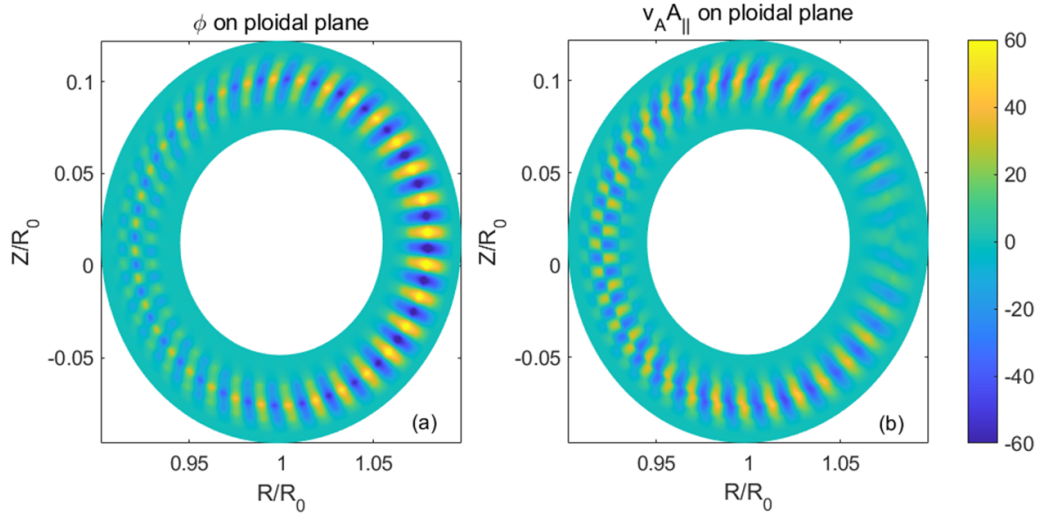


Figure 5. Mode structure of electrostatic potential (a) and parallel vector potential (b) at $\rho = 0.1 - 0.3$ at 20 s of shot 90949.

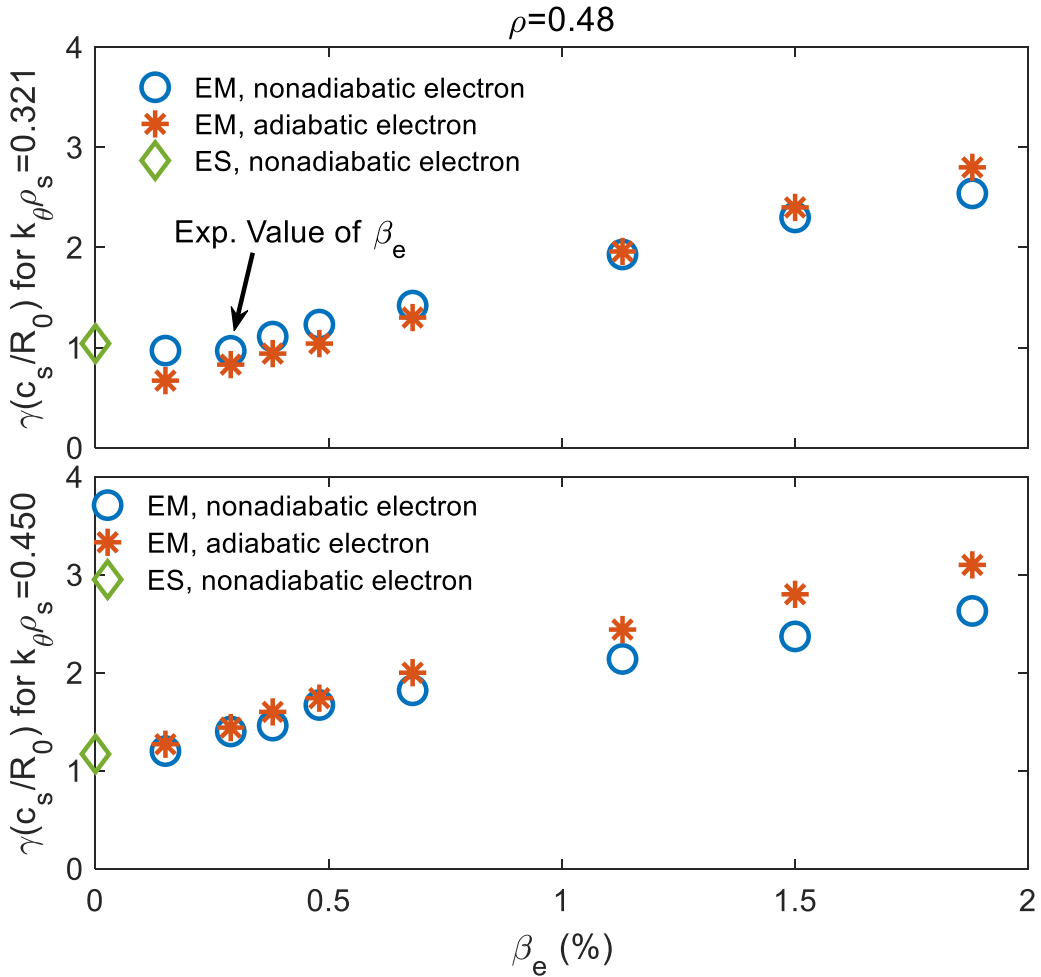


Figure 6. β_e dependence of the linear growth rate for $k_\theta \rho_s = 0.321$ (a) and $k_\theta \rho_s = 0.450$ (b) at $\rho = 0.48$ at 20 s of shot 90949.

of this electromagnetic instability is close to zero or positive. Early research based on kinetic theory demonstrates that the frequency of electromagnetic KBM is negative and the absolute value of the real frequency decreases with decreasing

T_i/T_e [30]. The T_i/T_e on axis of this high β_p discharge on EAST is 0.18.

To investigate the effects of temperature ratio on this electromagnetic instability, the temperature ratio is scanned by

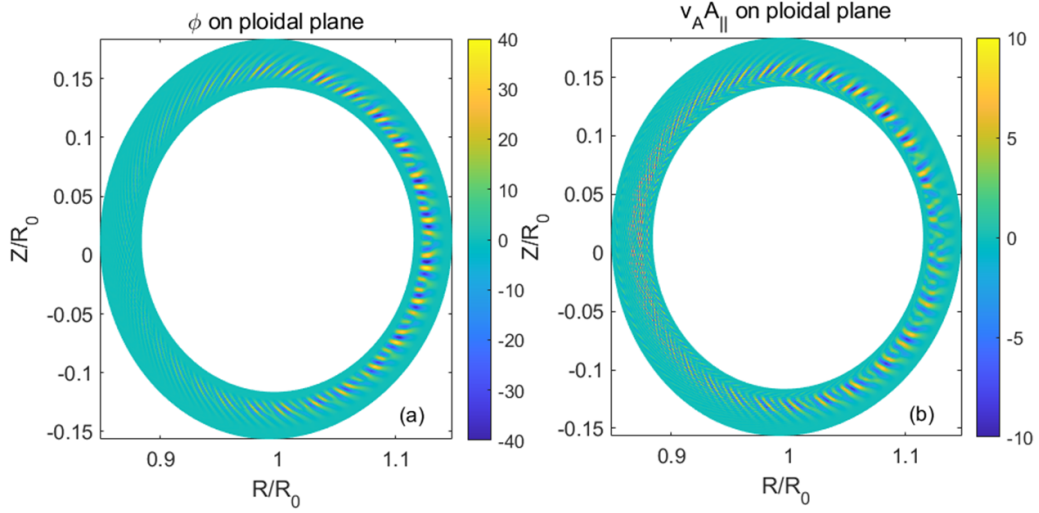


Figure 7. Mode structure of electrostatic potential (a) and parallel vector potential (b) at $\rho = 0.4 - 0.6$ at 20 s of shot 90949.

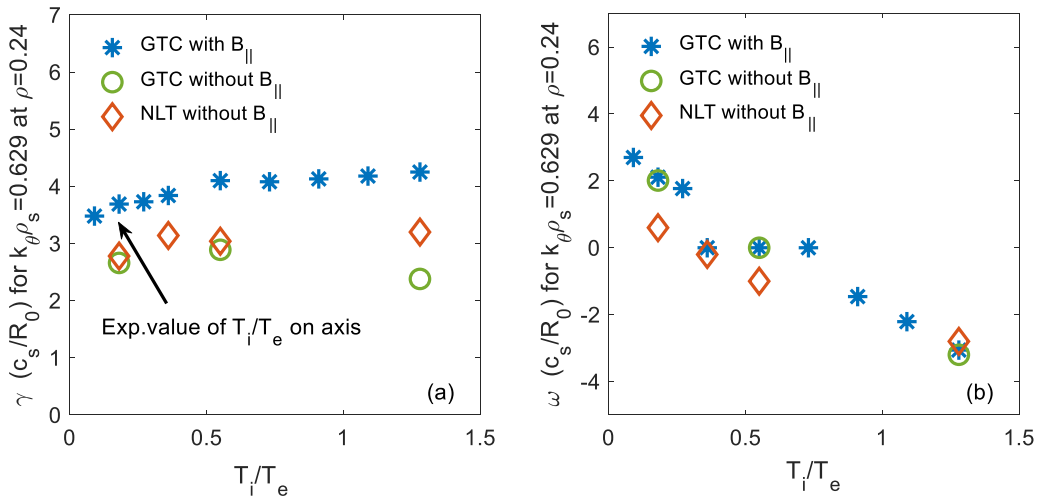


Figure 8. Ion–electron temperature ratio dependence of linear growth rate (a) and real frequency (b) for $k_\theta \rho_s = 0.629$ at $\rho = 0.24$ at 20 s of shot 90949. The blues stars and green circles denote growth rates and frequencies obtained by GTC simulations with and without $B_\parallel$, respectively. The red diamonds denote growth rates and frequencies obtained by NLT simulations without $B_\parallel$.

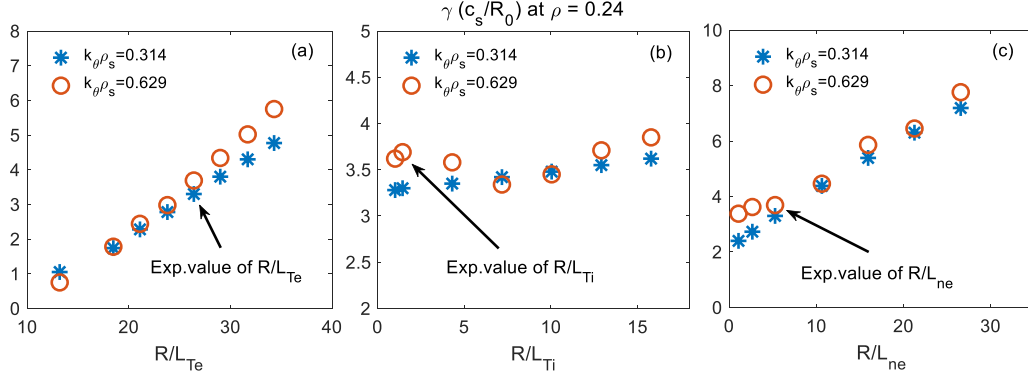
multiplying a constant on the ion temperature profile while keeping the electron temperature profile fixed, the results are shown in figure 8. It can be seen that growth rate of the instability is insensitive to T_i/T_e while the real frequency decreases from positive value to negative value with the increasing T_i/T_e . The ω calculated by situation using experimental profiles is about $2.0 c_s/R_0$ and reduces to nearly zero with the increasing T_i/T_e . When T_i/T_e exceeds 0.8, the ω reduces to negative value, this is consistent with the properties of conventional electromagnetic KBM. Since this instability observed in simulation using experimental parameters shows a variety of similarity with KBM (β_e dependence, mode structure of ϕ and $A_\parallel$, and non-sensitivity to trapped electron effects), we refer to this instability, which occurs at low ion–electron temperature ratio conditions and exhibits positive or nearly zero frequency, as the unconventional KBM (UKBM). Simulations without the parallel part of the perturbed magnetic field ($B_\parallel$) are also performed, the results are shown in green circles and green

stars in figure 8. It can be seen that the growth rate obtained by simulation without $B_\parallel$ is lower while the frequency is insensitive to $B_\parallel$, which are similar to the results in [22]. This indicates that $B_\parallel$ is not the key factor to the formation of UKBM.

Similar properties are also observed in the situation at $\rho = 0.48$, the frequencies of the UKBM in high β_e conditions change to negative value when T_i/T_e is increased to above one. In order to exclude numerical disturbances and prove the realism of the simulation results, simulations based on the same scenario using another gyrokinetic simulation code numerical lie transform (NLT) [31, 32] are performed. NLT is a global gyrokinetic code which uses semi-Lagrangian approach to solve the gyrokinetic equations. Results obtained by NLT electromagnetic simulations are given in figure 8, which prove that the UKBM with positive or nearly zero frequency is observed in low T_i/T_e condition and the frequency changes to negative value when T_i/T_e is increased to a higher

Table 2. Simulation results using analytical CBC-like profiles.

	Simulation parameters	Sign of frequency
Case 1	$R/L_{Te} = 6.9, R/L_{Ti} = 6.9, T_e/T_i = 1$	Negative
Case 2		None
Case 3	$R/L_{Te} = 15, R/L_{Ti} = 6.9, T_e/T_i = 5$	Positive
Case 4	$R/L_{Te} = 15, R/L_{Ti} = 15, T_e/T_i = 5$	Positive
Case 5	$R/L_{Te} = 15, R/L_{Ti} = 6.9, T_e/T_i = 0.5$	Negative

**Figure 9.** Parametric dependence of linear growth rate of dominant instabilities at $\rho = 0.24$ on electron temperature scale length (a), ion temperature scale length (b), and electron density scale length (c).

value. It should be noted that although the frequency obtained by NLT do not match well with the frequency obtained by GTC in some simulation cases, NLT results do prove that the UKBM with positive or nearly zero frequency exists in high T_e/T_i condition.

To further investigate the transition between UKBM and conventional KBM, several simulations using analytical cyclone base case (CBC)-like profiles are performed and the results are given in table 2. The temperature and density profiles are given by $f(\rho) = f_0 \exp(-\kappa_f \frac{a}{R_0} \Delta_f \tanh(\frac{\rho - \rho_0}{\Delta_f}))$, where f_0 is the temperature or density on axis, $\Delta_f = 0.3$ and $\rho_0 = 0.5$. By altering κ_f , we are able to change R/L_f . In all these simulation cases, $T_{e0} = 2223$ eV, $R/L_{ne} = 2.2$, and $n_{e0} = 9 \times 10^{19} \text{ m}^{-3}$, so $\beta_{e0} = \frac{8\pi n_{e0} T_{e0}}{B^2}$ is fixed as 1.99%, which is consistent with the CBC standard case for KBM in previous work [14]. Table 2 shows the sign of the frequency of mode with $n = 10$ and $m = 14$ under different simulation cases. Case 1 is the standard CBC case and the result shows the conventional KBM with negative frequency. Ion temperature are modified to $0.2 \times T_e$ in case 2 and the result shows that none of the instabilities are excited in this situation. Then we increase R/L_{Te} to 15 in case 3 and instability with positive frequency is observed. Electrostatic simulation using the same parameters as that in case 3 is also performed and the growth rate obtained by ES simulation ($0.64 c_s/R_0$) is much lower than the growth rate obtained by EM simulation ($3.2 c_s/R_0$), which proves that the instability in case 3 is UKBM. These indicate that UKBM with positive frequency needs a high value of R/L_{Te} to be unstable. In case 4, R/L_{Ti} is increased to 15 and the frequency of the mode is still positive, which indicates that R/L_{Ti} is not the key issue of transition between UKBM to KBM. In case 5, T_i is modified to $2 \times T_e$ and R/L_{Ti} is set as 6.9. The frequency of the mode is negative, which means UKBM has transitioned to

conventional KBM. Simulation results using analytical CBC-like profiles provide further evidence of the authenticity of UKBM with positive or nearly zero frequency observed in the high T_e/T_i conditions in high β_p discharge on EAST.

3.4. Temperature and density scale length scan

To further investigate the properties of this UKBM observed in this two radial position, ion density scale length, electron temperature and density scale length scan are performed. The profiles are modified through multiplying a coefficient ($e^{k(\rho - \rho_r)}$, where k is a constant, ρ is the normalized minor radius and ρ_r is 0.24 or 0.48) to the original profile. Figure 9 shows the parametric dependence of growth rate on R/L_{Te} , R/L_{Ti} and R/L_{ne} at $\rho = 0.24$. It can be seen that R/L_{Te} and R/L_{ne} destabilize the instability and R/L_{Ti} shows little effects on the growth rate. These indicate that the driven mechanism of UKBM is the electron pressure gradient when β_e exceeds the critical of TEM-UKBM transition.

As shown in figure 3, the frequencies of modes with $k_\theta \rho_s = 0.314$ and $k_\theta \rho_s = 0.629$ are nearly zero and finite positive, respectively. Simulation results shown in figures 4 and 9 indicate that the properties of UKBM with nearly zero frequency are similar with that with finite positive frequency.

Same parametric scan simulations are also performed at $\rho = 0.48$, as shown in figure 10. The R/L_{Te} still destabilize the instabilities while the growth rate is slightly decreased with increasing R/L_{Ti} . This is consistent with the properties of TEM that we observed in our previous research [8]. As mentioned in section 3.2, the experimental value of β_e is close to the transition threshold between the TEM and UKBM. This could be the reason that the dominant instability here shows similar R/L_{Ti} dependence with TEM. When performing R/L_{ne}

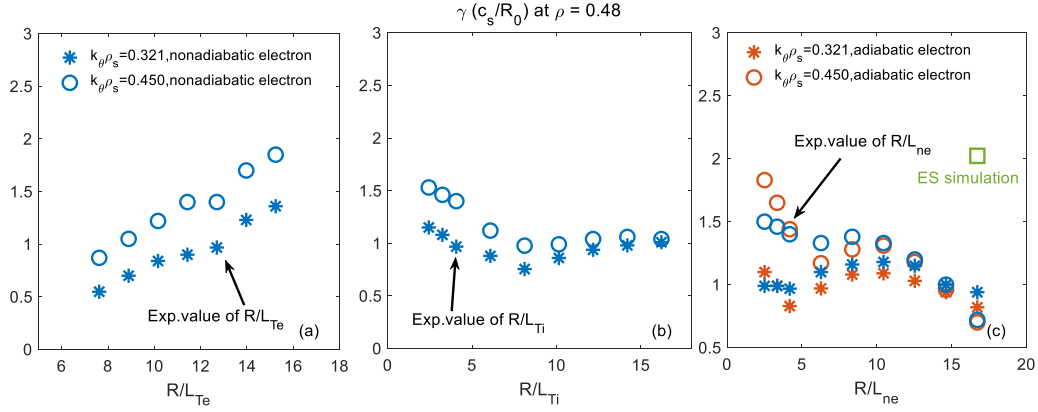


Figure 10. Parametric dependence of linear growth rate of dominant instabilities at $\rho = 0.48$ on electron temperature scale length (a), ion temperature scale length (b), and electron density scale length (c). The green box in (c) stands for γ for $k_\theta \rho_s = 0.450$ obtained by electrostatic simulation.

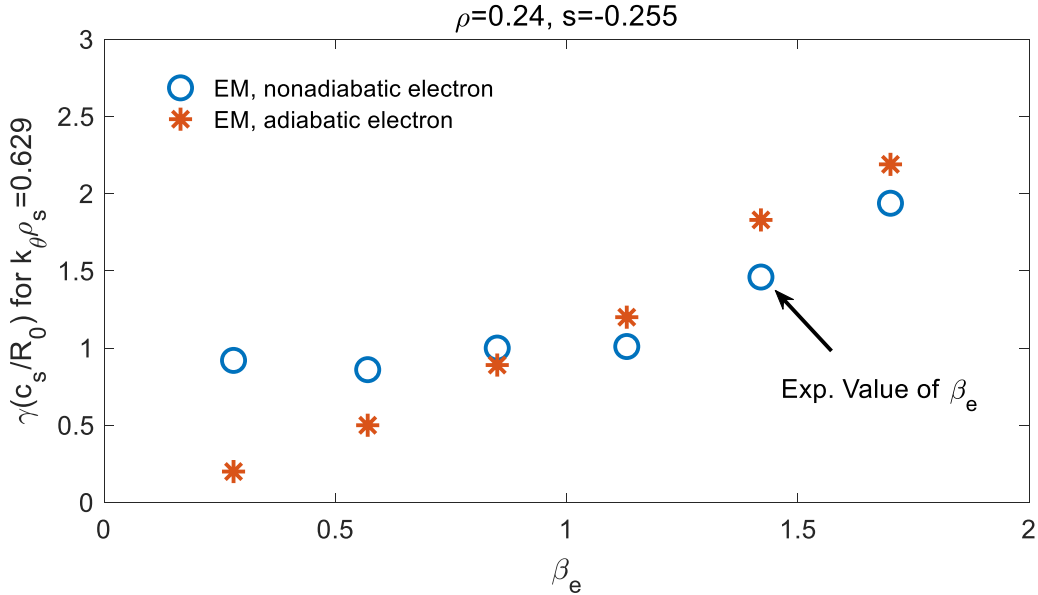


Figure 11. β_e dependence of the linear growth rate for $k_\theta \rho_s = 0.629$ at $\rho = 0.24$ at 20 s of shot 90949 with $s = -0.255$.

scan, it is found that the increasing R/L_{ne} has little effects on the growth rate of instability for $k_\theta \rho_s = 0.321$ while the growth rate of instability for $k_\theta \rho_s = 0.450$ decreases obviously with the increasing R/L_{ne} , as seen in figure 10(c). This property is the opposite of that of TEM in our previous work or UKBM observed at $\rho = 0.24$. Simulations using adiabatic electron model are also performed and the growth rate is close to that obtained by simulations using nonadiabatic electron model, this indicates the trapped electron effects is not essential for this instability. We also performed electrostatic simulations using profiles with $R/L_{ne} = 16.72$ and the result is shown in green box in figure 10(c). Electrostatic simulation points out that the dominant instability at this situation is TEM and the growth rate is $2.12 c_s/R_0$, which means the dominant instability obtained by electromagnetic simulation is stabilized by electromagnetic effects and the decreasing growth rate with increasing R/L_{ne} is not the property of electrostatic TEM. Therefore, it can be inferred that this trend of decreasing

growth rate with R/L_{ne} is a property of UKBM when β_e is close to the threshold value of TEM-UKBM transition. The driven mechanism of UKBM near β_e threshold is mainly η_e ($\eta_e = \frac{R/L_{Te}}{R/L_{ne}}$) rather than electron pressure gradient.

3.5. Reversed magnetic shear

One of the way to achieve the high performance ITB state at high pressure gradient together with low transport, which is often referred as second stability regime, is making a stable pass from the first to second stability regime though low or reversed magnetic shear [33]. To investigate the properties of UKBM in reversed magnetic shear condition, same β_e scan as figure 4(b) is performed with the magnetic shear fixed to -0.255 , the results are given in figure 11. Here, the safety factor profile is multiplied by a coefficient a coefficient ($e^{-2.5(\rho-0.24)}$, where ρ is the normalized minor radius). So

the local value of magnetic shear at $\rho = 0.24$ is modified to -0.255 while the value of safety factor at this positions is unchanged. Comparing figure 4(b) with figure 11, it can be seen that the growth rate corresponding to each β_e value is significantly lower in the reversed magnetic shear condition, which means the reversed magnetic shear has a significant stabilize effect on UKBM. It can be also seen that in simulations using nonadiabatic electron model, the growth rate increases with β_e obviously when $\beta_e > 0.8\%$ in figure 4(b) while the growth rate increases with β_e obviously when $\beta_e > 1.1\%$ in figure 11. This indicates that the β_e threshold of TEM-UKBM transition is increased under reversed magnetic shear condition. These results show that the stable pass from first to second stability regime through reversed magnetic shear is also available for high β_p discharge on EAST.

4. Conclusions

The high β_p scenarios are improved to higher plasma performance on EAST since the international atomic energy agency (IAEA) in 2018. Experimental data of one typical high β_p discharge is chosen to perform gyrokinetic simulations to investigate the properties of the electromagnetic instabilities on these high β_p discharges on EAST.

The ion-scale linear electromagnetic simulations are performed focus on two radial positions: $\rho = 0.24$ and 0.48 . The R/L_{Te} reaches maximum value at $\rho = 0.24$ and R/L_{Ti} reaches a peak and $R/L_{Ti} \approx R/L_{ne}$ at $\rho = 0.48$. $k_\theta \rho_s$ scan shows that the growth rate peaks at $k_\theta \rho_s = 0.629$ and 0.450 at $\rho = 0.24$ and 0.48 , respectively. Considering the toroidal mode number of the dominant instability in nonlinear simulations is often lower compares to that in the linear simulations, another instability with lower $k_\theta \rho_s$ is also chosen to perform parametric scan at each radial position. The β_e scan and mode structure show that the dominant instability at $\rho = 0.24$ is a kind of electromagnetic instability with similar β_e dependence to KBM and exhibits typical ballooning mode structure. And the frequencies of these instabilities are positive or close to zero. T_i/T_e scan demonstrates that these positive or nearly zero frequencies are due to the low T_i/T_e in this high β_p discharge on EAST. This mode turns to conventional KBM with negative frequency when T_i/T_e exceeds a threshold. This instability which occurs at low T_i/T_e conditions and exhibits positive or nearly zero frequency is recognized as UKBM. The temperature and density scale length scan shows that the driven mechanism of UKBM is electron pressure gradient when β_e exceeds the threshold of TEM-UKBM transition.

Situation at $\rho = 0.48$ is more completed. The β_e scan shows that the experimental β_e at $\rho = 0.48$ is close to the threshold of TEM-UKBM transition and the mode structure shows that the electromagnetic part of the instability here is much weaker than electrostatic part. These result in the instability at $\rho = 0.48$ shows the properties of both electrostatic TEM and electromagnetic UKBM. The growth rate of this mode is close to that of TEM calculated by electrostatic simulation and the frequency of this mode is close to zero, which is the property of UKBM. The temperature and density scale length scan also proves that. The γ dependence on R/L_{Ti} is similar to that of

TEM. It is found that the R/L_{ne} dependence is different from that at $\rho = 0.24$ and the electrostatic simulation shows this is not the property of electrostatic TEM, which indicates that the decreasing γ with R/L_{ne} is due to UKBM. It is proposed that the driven mechanism of UKBM changes from electron pressure gradient to η_e when β_e is close to the threshold of TEM-UKBM transition.

Effects of reversed magnetic shear on UKBM is also investigated in this work. The results show that the reversed magnetic shear partly stabilizes the UKBM and increases the β_e threshold of TEM-UKBM transition. This proves the way through reversed magnetic shear to pass from the first to second stability regime is available in high β_p scenarios on EAST. In this work, we mainly focus on the linear properties of the electromagnetic instabilities in the β_p discharge on EAST, the nonlinear transport level caused by this UKBM is still unclear. Besides, the collision effects are neglected since the main focus of this work is investigating the effects of plasma temperature and density on the UKBM. Simulations with collision effects and nonlinear electromagnetic simulations could be left to future works.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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