

PAPER

Study of turbulence in the high β_p discharge using only RF heating on EAST

To cite this article: S Y Zheng *et al* 2022 *Plasma Phys. Control. Fusion* **64** 045017

View the [article online](#) for updates and enhancements.

You may also like

- [Gyrokinetic simulation of electromagnetic instabilities in the high \$\beta_p\$ scenario on EAST](#)
S Y Zheng, D B Zhang, L M Yu et al.
- [Simulation on the transition of electrostatic instabilities in EAST steady-state scenario](#)
Lianjie MA, , Debing ZHANG et al.
- [Modeling and advances in the high bootstrap fraction regime on EAST towards the steady-state operation](#)
M.Q. Wu, G.Q. Li, J.P. Qian et al.

Study of turbulence in the high β_p discharge using only RF heating on EAST

S Y Zheng¹ , D B Zhang^{1,*} , E B Xue¹ , L M Yu¹ , X M Zhang^{1,*}, J Huang², Y Xiao³ , M Q Wu⁴ , X Z Gong² and EAST Team²

¹ Department of Physics, East China University of Science and Technology, Shanghai 200237, People's Republic of China

² Institute of Plasma Physics, Chinese Academy of science, Hefei 230031, People's Republic of China

³ Institute for Fusion Theory and Simulation, Zhejiang University, Hangzhou 310027, People's Republic of China

⁴ Advanced Energy Research Center, Shenzhen University, Shenzhen 518060, People's Republic of China

E-mail: zdbing@ecust.edu.cn and zhangxm@ecust.edu.cn

Received 22 July 2021, revised 11 January 2022

Accepted for publication 13 January 2022

Published 28 February 2022



Abstract

High poloidal beta scenarios with a favorable energy confinement ($\beta_p \sim 1.9$, $H_{98y2} \sim 1.4$) have been achieved on the Experimental Advanced Superconducting Tokamak using only radio frequency wave heating. Gyrokinetic simulations are carried out with experimental plasma parameters and tokamak equilibrium data of a typical high β_p discharge using the gyrokinetic toroidal code. Linear simulations show that electron-temperature scale length and electron-density scale length destabilize the turbulence, collision effects stabilize the turbulence, and the instability propagates in the electron diamagnetic direction. These properties indicate that the dominant instability in the core of high β_p plasma is a collisionless trapped electron mode. Ion thermal diffusivity, calculated by nonlinear gyrokinetic simulations, is consistent with the experimental value, in which the electron collision effects play an important role. Further analyses show that instabilities with $k_\theta \rho_s > 0.38$ are suppressed by collision effects and collision effects reduce the radial correlation length of turbulence, resulting in the suppression of the turbulence.

Keywords: high poloidal beta, gyrokinetic simulation, turbulence, transport

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

1. Introduction

The high poloidal beta (β_p) scenario is an attractive candidate for steady-state operations in future burning-plasma devices, since the bootstrap current fraction f_{BS} is proportional to β_p , which reduces the demand on external current drive [1]. A high β_p scenario is also associated with a high edge safety factor q_{95} , which reduces disruptivity [2]. Here, β_p is defined as the ratio of the 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.

The high β_p steady-state scenario was first developed on the JT-60U with a high confinement ($H_{98y2} \sim 1.7$) and reactor-relevant parameter regime [3]. DIII-D was investigating a range of high β_p solutions, building on high q_{95} and high rotation, which reached a high β limit with $\beta_N \sim \beta_p > 3.0$ [4, 5]. The DIII-D/Experimental Advanced Superconducting Tokamak (EAST) joint experiments performed in the DIII-D high β_p regime reached a high confinement ($H_{98} > 1.5$) at near zero rotation, with internal transport barriers (ITBs) at a large minor radius [6]. Recent experiments on DIII-D have extended the high β_p regime to lower q_{95} ($q_{95} \sim 6.0$) and low rotation, which

* Authors to whom any correspondence should be addressed.

is expected in the International Thermonuclear Experimental Reactor (ITER) plasma, due to the low collisionality [7, 8]. The high β_p scenario is also one of the research focuses of the EAST. High β_p operation regimes with high confinement and performance were achieved using only radio frequency (RF) wave heating or together with neutral beam injection (NBI) [9, 10].

Since the transport level in high β_p discharges is usually far above neoclassical level, understanding the turbulence properties and the turbulent transport in these discharges is vital to improving plasma performance. Gyrokinetic simulation could provide insights into the process. Gyrokinetic simulations suggest that the instabilities remaining in lower q_{95} , high β_p plasma in the DIII-D are trapped electron mode (TEM) in the core and ITB peak gradient region, electron temperature gradient mode (ETG) in the ITB peak gradient region and at the ITB foot, and ion temperature gradient mode (ITG) at the ITB foot [11]. It is shown that ITG drives the ion heat flux and part of the electron heat flux in H-mode experiments on the ASDEX Upgrade tokamak [12]. A validation is performed for a modest-beta NSTX NBI-heated H-mode discharge using the gyrokinetic code GYRO, that predicts that ETG drives the electron thermal transport [13].

In this paper, turbulence in high β_p discharge in the EAST, during RF heating only, is investigated by gyrokinetic simulations. The rest of this paper is organized as follows. The experimental conditions of the high- β_p discharge are introduced in section 2. Section 3 describes the simulation model and setup. The results given by gyrokinetic simulations are presented in section 4 and the conclusions are given in section 5.

2. Experimental setup

The EAST is the first fully superconducting tokamak with an ITER-like divertor configuration and heating scheme. The major goal of the EAST device is to achieve stable long-pulse, high performance, fully non-inductive plasma operation, and to provide a theoretical basis for future large-scale fusion devices. In recent years, a high β_p scenario with high confinement and high density has become the research focus of the EAST device. In the 2018 EAST experimental campaign, a set of steady-state discharges with high confinement and high β_p was achieved. One typical discharge (81 481) is chosen for study in this paper. The main parameters of shot 81 481 are as follows: the plasma current I_p is 400 kA; the loop voltage is near zero and the line-averaged electron density is $4.3 \times 10^{19} \text{ m}^{-3}$. β_p is about 1.9 and H_{98y2} is up to 1.3. The auxiliary heating systems include a 2.6 MW lower hybrid wave (LHW), 1.0 MW of electron cyclotron resonance heating (ECRH) and 0.6 MW of ion cyclotron resonance heating (ICRF), as shown in figure 1. The LHWs are injected at 1 and 2 s, the ECRH is injected at 2.5 s, and the ICRF is injected at 6.3 s.

The injection of LHW significantly raises β_p to about 1.5. After the injection of ECRH, β_p reaches about 1.9 and remains relatively stable. This work focuses on the turbulence properties and turbulent transport in the core region of shot 81 481 at 5.3 s, as auxiliary heating power and plasma parameters are

stable at this time slice, as shown by the green dotted line in figure 1(e). The gyrokinetic simulations utilize experimental plasma profiles at 5.3 s and real magnetic equilibrium obtained by equilibrium fitting code (EFIT) [14], as shown in figure 2. Here, ρ is the normalized minor radius. The electron temperature (T_e) is measured by the Thomson scattering (TS) diagnostic [15], the ion temperature (T_i) is measured by charge-exchange recombination spectroscopy [16] and the electron density (n_e) is measured by TS and reflectometers [17]. The safety factor (q) profile is obtained by using the Faraday rotation by polarimeter-interferometer as an additional constraint in the EFIT code [18].

3. Simulation model and setup

In this work, we investigate the turbulence and transport of a high β_p discharge on the EAST using the gyrokinetic simulation code (GTC) [19, 20]. GTC is a global three-dimensional particle simulation code using the particle in cell method, specially designed for tokamak physics. This code uses gyrokinetic methods to describe ions, and a fluid-kinetic hybrid electron model is used to improve the computational efficiency of the simulation [21]. 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. 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. The collision effect is considered in GTC, where a pitch angle scattering operator is used for electron–ion collisions, and the Fokker–Planck operator is used for electron–electron collisions and ion–ion collisions [22, 23].

The assumption of gradient-driven turbulence is generally adopted in current gyrokinetic simulations, so from the perspective of simulation, we are concerned about the scale length of the experimental parameters. It is also worth mentioning that a source term is used in GTC to keep the profiles fixed throughout the simulations [24]. The temperature and density scale length and magnetic shear (s) at 5.3 s are shown in figure 3. Seen from figure 3, the maximum value of electron-temperature scale length (R/L_{Te}) is 23.15, which is much larger than the electron-density scale length (R/L_{ne}) and ion-temperature scale length (R/L_{Ti}) at all radial positions. Therefore, the simulations focus on where R/L_{Te} reaches maximum value, namely at $\rho = 0.23$, where $R/L_{Ti} = 2.07$, $R/L_{ne} = 2.08$, and $s = 0.27$.

After performing a series of convergence tests, some of the parameters adopted in the simulations are as follows: the simulation region is between $\rho = 0.02$ and 0.7, fixed boundary conditions are applied on both sides of the radial domain and periodic boundary conditions are applied in poloidal and toroidal directions. The major radius $R_0 = 1.9$ m, the minor radius $a = 0.4$ m, the toroidal magnetic field $B_T = 2.5$ T, and the simulation time step $t_{\text{step}} = 0.01R_0/c_s$, where c_s is the ion acoustic velocity (2000 steps for linear simulations and 10 000 steps for nonlinear simulations). The radial grids are 180, the poloidal grid length is nearly equal to the radial grid

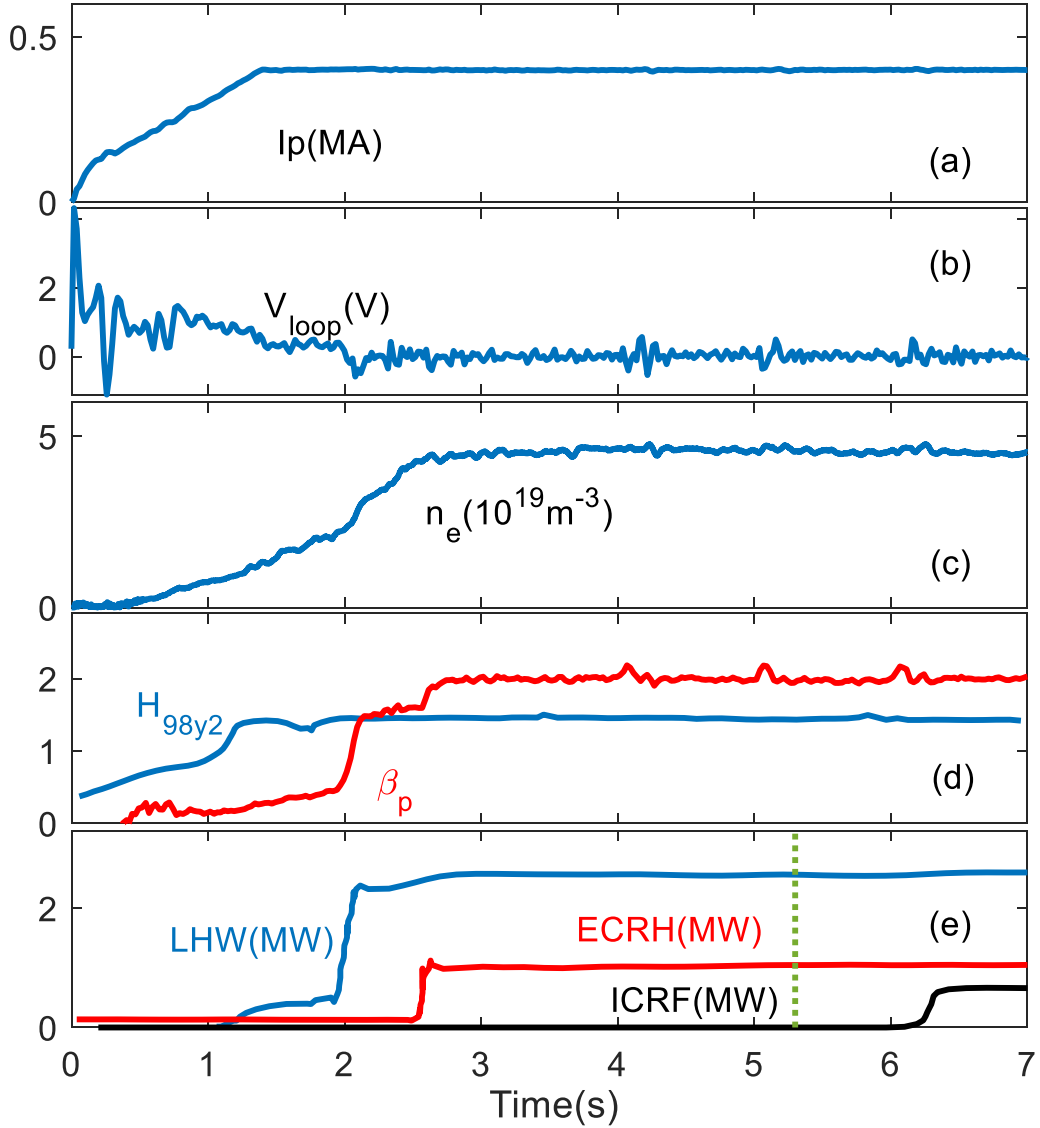


Figure 1. Time history of shot 81 481 on the EAST: (a) plasma current, (b) loop voltage, (c) line-averaged electron density, (d) poloidal beta and H_{98y2} energy confinement factor, (e) auxiliary heating powers of LHW, ECRH, and ICRF.

length and the toroidal grids are 32. The main ion is deuterium ($m_D/m_e = 3672$).

The electron plasma beta ($\beta_e = \frac{8\pi n_{e0} T_{e0}}{B^2}$) in our simulations is 1.88%. In all simulations in this article, the core electron temperature and electron density are fixed, so β_e is fixed. Linear electromagnetic simulation is performed, but the result shows that the kinetic ballooning mode is not observed, so electrostatic simulation is mainly taken out for this high β_p discharge.

4. Simulation results and discussion

4.1. Linear simulations

The linear simulation is performed at ion-scale ($0.1 < k_\theta \rho_s < 1.0$) and the turbulence spectrum is shown in figure 4. The linear growth rate γ peaks at $k_\theta \rho_s = 0.38$ and the real frequency ω decreases with $k_\theta \rho_s$, as seen from figure 4. Here k_θ is the

poloidal wave vector and $\rho_s = \sqrt{T_e m_i} / e B_0$ is the ion-sound Larmor radius. Therefore, the instability where $k_\theta \rho_s = 0.38$ is the dominant instability at $\rho = 0.23$ at 5.3 s of shot 81 481. It can be seen from figure 4(b) that in this case, the frequencies of all ion-scale instabilities are positive. Here we consider that an instability with positive frequency propagates in the electron diamagnetic direction. Note that the dependency of ω with $k_\theta \rho_s$ is in contrast with previous results in the cyclone base case [25], but it is consistent with the results in a DIII-D discharge [11].

To further reveal the kind of turbulence in this situation, parameter scans are carried out. The profiles are modified through multiplying a coefficient ($e^{k(\rho-0.23)}$, where k is a constant and ρ is the normalized minor radius) to the original profile. Figure 5 demonstrates the parametric dependence of the linear growth rate γ . γ , obtained from the simulation performed with the experimental profile, is also shown using star points in figure 5 for comparison. γ decreases little

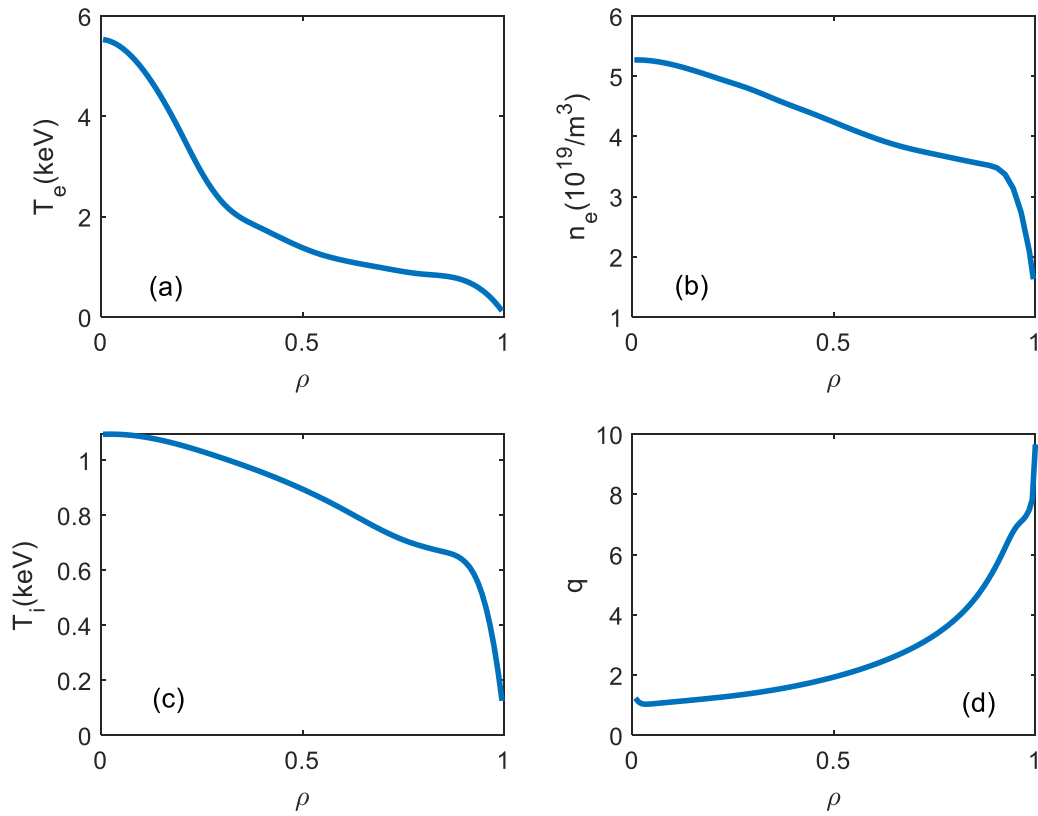


Figure 2. Radial profiles of electron temperature (a), electron density (b), ion temperature (c), and safety factor (d) of shot 81 481.

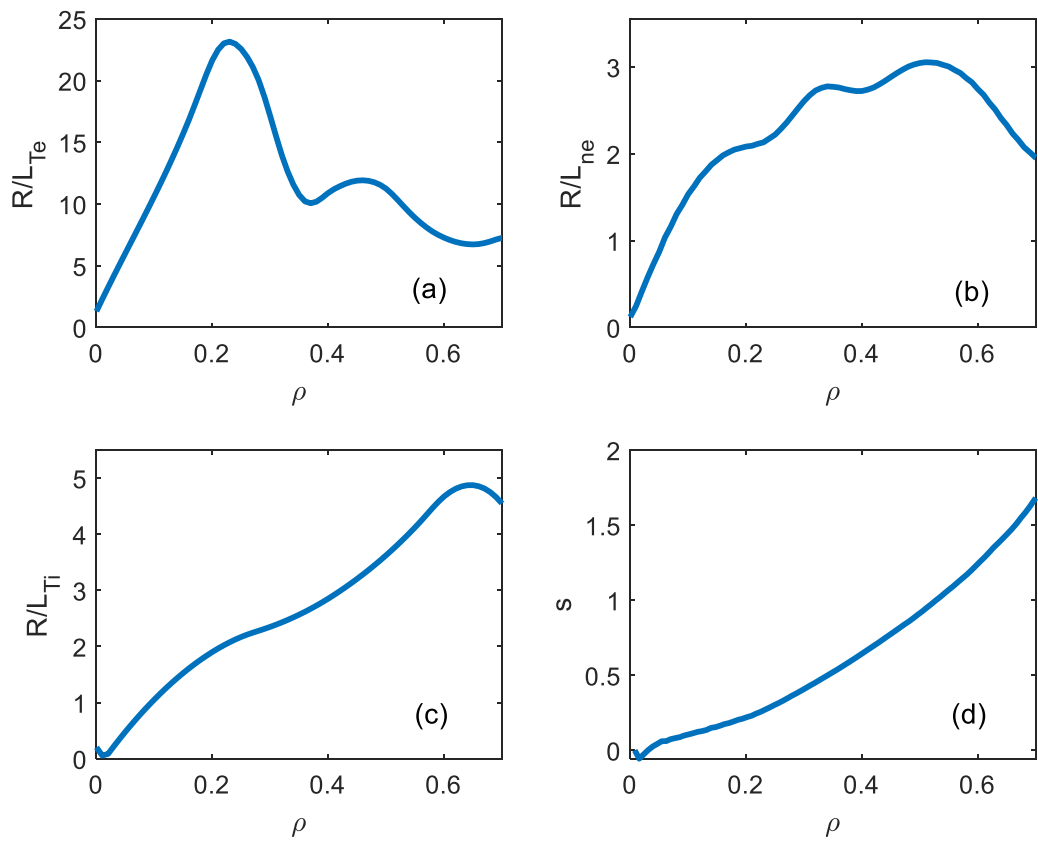


Figure 3. Radial profiles of electron-temperature scale length (a), electron-density scale length (b), ion-temperature scale length (c), and magnetic shear (d) at 5.3 s of shot No. 81 481.

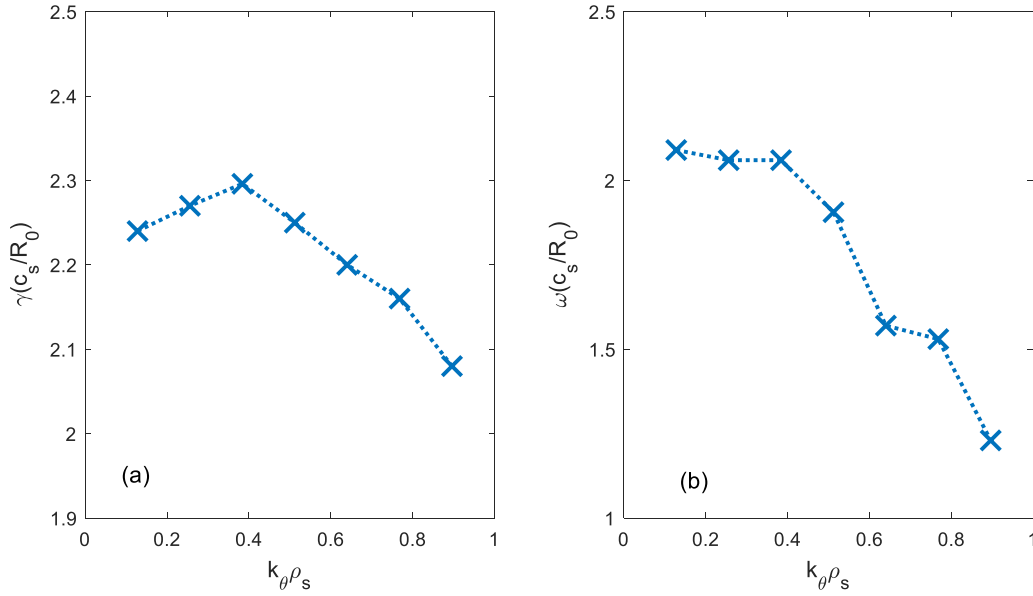


Figure 4. Turbulence linear growth rate (a) and frequency spectrum (b) for different $k_\theta \rho_s$ at $\rho = 0.23$ at 5.3 s of shot 81 481.

as R/L_{Ti} increases, but it increases obviously as R/L_{ne} and R/L_{Te} increase, which means R/L_{Ti} has a slight stabilizing effect, while R/L_{ne} and R/L_{Te} have a significant destabilizing effect. Simulation with collision effects is also performed, and γ where $k_\theta \rho_s = 0.38$ is reduced to $0.9 c_s/R_0$. This indicates that this mode can be partially stabilized by collision effects. These properties are consistent with collisionless trapped electron mode (CTEM) in previous studies [11, 26], which indicates that the dominant instability in this situation is CTEM. It is also found that γ increases about 58% when R/L_{Te} increases about 60%, while γ increases about 53% when R/L_{ne} increases about 1140%. So R/L_{Te} is the main drive mechanism for CTEM in our simulations. During the R/L_{Ti} scan, two peaks are observed in the frequency spectrum in some cases, which indicates that the ITG may be unstable. Therefore, simulations using the adiabatic electron model are also performed in the R/L_{Ti} scan. The adiabatic electron model only preserves the low-order fluid part of the electronic response and the non-adiabatic electron model preserves all the electronic response. In simulations using the adiabatic electron model, only the ITG mode exists. The results show that the ITG mode becomes unstable after R/L_{Ti} exceeds 4, while the growth rate of the ITG is much lower than the growth rate calculated by the non-adiabatic electron model for the same R/L_{Ti} values.

Two simulation cases with $R/L_{Ti} = R/L_{Te}$ are also taken out with the non-adiabatic electron model and adiabatic electron model, by replacing the ion temperature profile with the electron temperature profile, and the results are compared in table 1. In the first case, the ion core temperature is fixed by multiplying the ion temperature profile by a coefficient. ($T_{i0} = 1.1$ keV) The Growth rate given by the adiabatic electron model is 0.655, which is one-third of the growth rate given by the non-adiabatic electron model. In the second case, the ion temperature profile is exactly the same as the electron temperature profile ($T_{i0} = 5.5$ keV). The growth rate given by the

adiabatic electron model increases to 1.43 and reaches 70% of that given by the non-adiabatic electron model, which suggests that the decrease of the Te/Ti ratio from 5 to 1 destabilizes the ITG mode. Considering the destabilizing effect of the trapped electron effects on ITG [25], ITG may dominate over the TEM in this case.

The frequency spectra of the instabilities at $\rho = 0.23$ in three simulations are given in figure 6. The sign of the peak abscissa indicates the direction of propagation of the instability. Figures 6(a), (c) and (d) exhibit only one peak, suggesting that the dominant instabilities in these two cases are CTEM or ITG. There are two peaks in figure 6(b), which is consistent with figure 5(a) that ITG becomes unstable. A similar phenomenon is observed in simulations with $R/L_{Ti} > 4$ and occurring mainly in instabilities where $k_\theta \rho_s = 0.38$. It is proposed that a kind of TEM/ITG hybrid mode exists under these situations. It is also found that this phenomenon is likely to be observed in instabilities where $k_\theta \rho_s < 0.38$ with the increase of R/L_{Ti} . In the simulations with $R/L_{Ti} > 9$, the peak abscissa of instabilities where $k_\theta \rho_s > 0.38$ are negative, which indicates that these modes are ITG. This is consistent with the results of simulations using the adiabatic electron model, that the maximum value of the growth rate of ITG mainly occurs in $k_\theta \rho_s = 0.7 \sim 0.8$. If the ion temperature profile is steepened by auxiliary heating, ITG becomes more important. Figure 5(a) and table 1 show that CTEM is still the dominant instability in the plasma when R/L_{Ti} is lower than R/L_{Te} . After R/L_{Ti} approaches or exceeds R/L_{Te} , a transition from CTEM to ITG mode may occur, which could have an impact on the thermal transport.

4.2. Nonlinear simulations

Sets of nonlinear simulations are performed to investigate the turbulent transport in high β_p discharge on the EAST. First,

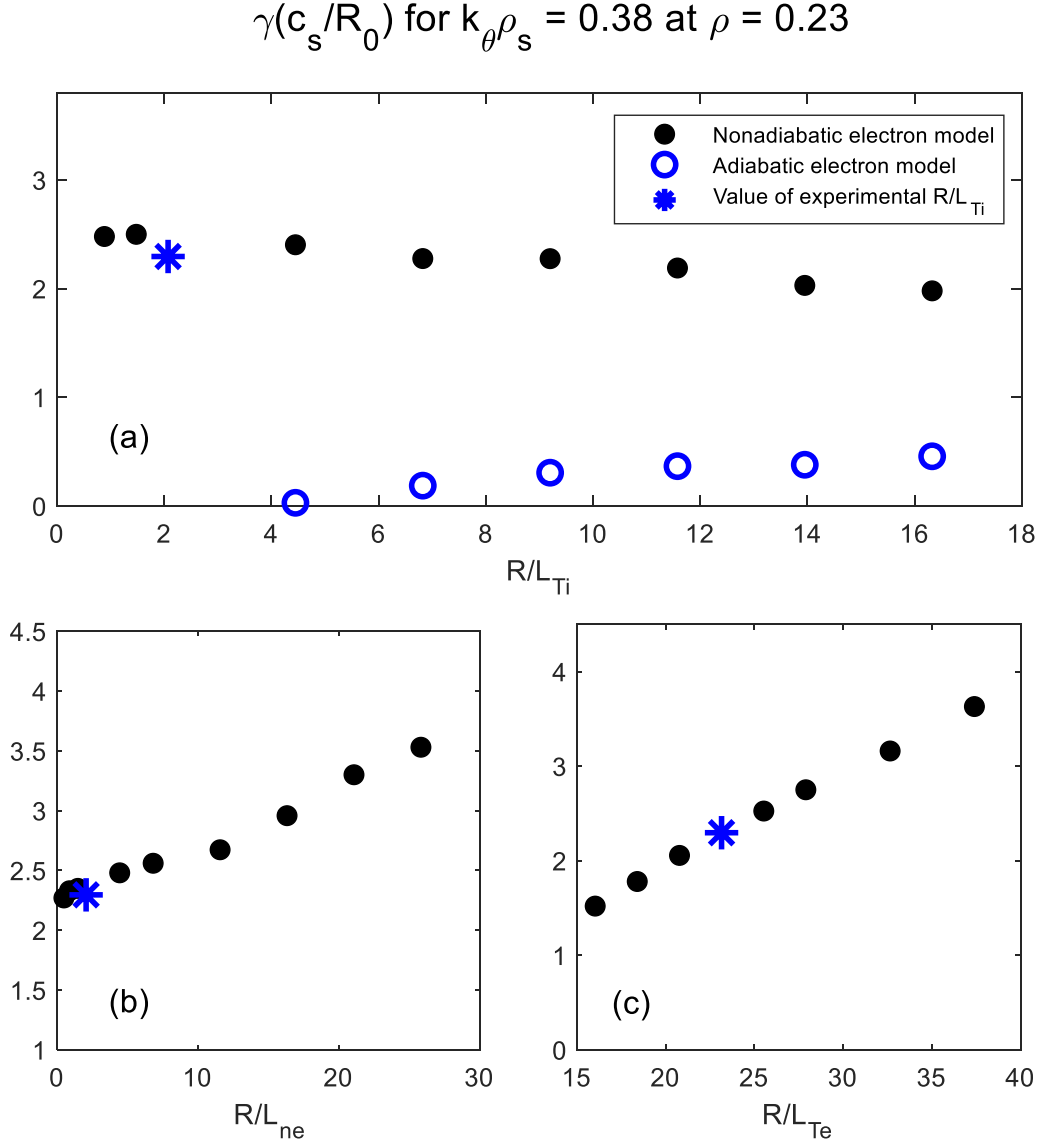


Figure 5. Parametric dependence of the linear growth rate of the mode with $k_\theta \rho_s = 0.38$ on ion-temperature scale length (a), electron-density scale length (b), and electron-temperature scale length (c). The blue stars indicate results performed with experimental profiles.

Table 1. Growth rate (c_s/R_0) with different electron model simulation cases when $R/L_{Ti} = R/L_{Te}$.

	R/L_{Ti}	γ (Nonadiabatic model)	γ (Adiabatic model)
$Ti_0 = 1.1 \text{ keV}$	23.15	1.79	0.655
$Ti_0 = 5.5 \text{ keV}$	23.15	2.02	1.43

a simulation using an experimental profile without collision effects ($R/L_{Te} = 23.15$ w/o coll) is carried out. Some convergence tests are performed and the results show that the value of the ion thermal transport diffusivity (χ_i) decreases little after $80 R_0/c_s$. The average value of χ_i decreases less than 4% after extending the simulation time by 40%. Considering the noise accumulation and the time cost of the simulation, the simulation time is set to $100 R_0/c_s$. The time evolution of the ion

thermal transport diffusivity in two simulation cases is given in figure 7. Apparently, the electron collision effects decrease the ion thermal transport diffusivity. The ion thermal diffusivity and potential given in the following text are the average values of $80 \sim 100 R_0/c_s$. However, the average ion thermal turbulent transport diffusivity during this period in the simulation without collision effects is $7.7 \text{ m}^2 \text{ s}^{-1}$, which is much higher than the experimental value ($1.19 \text{ m}^2 \text{ s}^{-1}$, calculated by TRANSP [27]), as can be seen in figure 8.

Based on this case, we modify some simulation parameters, including, ion collision effects, and electron collision effects, the main turbulence drive mechanism (R/L_{Te}), as collision effects are well known with the significant suppression of TEM. Figure 8 and table 2 show the ion and electron thermal transport diffusivity calculated by gyrokinetic simulations in different simulation cases and experimental values given by TRANSP. The TS diagnostic measures core electron

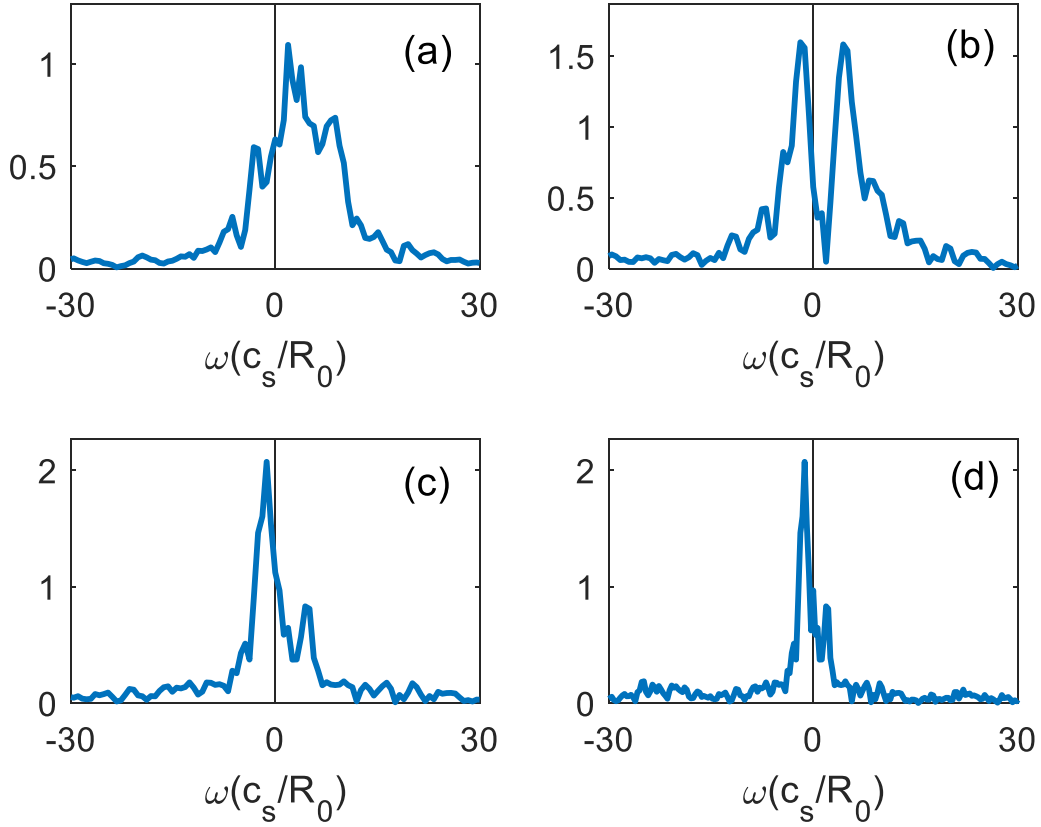


Figure 6. The frequency spectrum of the instabilities for $k_\theta \rho_s = 0.38$ in three simulations: (a) $R/L_{Ti} = 2.07$, $R/L_{Te} = 23.15$ (Exp. value), (b) $R/L_{Ti} = 16.32$, $R/L_{Te} = 23.15$ and (c) $R/L_{Ti} = R/L_{Te} = 23.15$, $Ti_0 = 1.1$ keV, (d) $R/L_{Ti} = R/L_{Te} = 23.15$, $Ti_0 = Te_0 = 5.5$ keV.

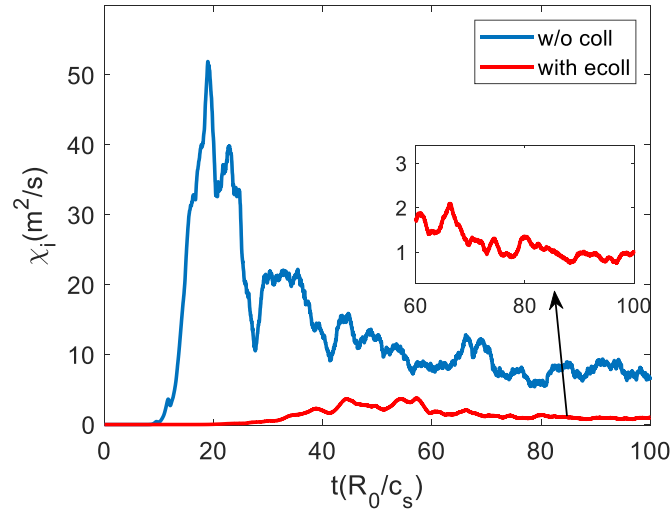


Figure 7. Time evolution of the ion thermal transport diffusivity as given by GTC simulations, with and without electron collision effects. Results with electron collision effects after $60 R_0/c_s$ are amplified in the box.

temperature with an error of about 20%. By reducing R/L_{Te} within the error range, χ_i can be declined to $6.15 \text{ m}^2 \text{ s}^{-1}$, but it is still higher than the experimental value. After considering the ion collision effects in the base case ($R/L_{Te} = 23.15$, w/o coll), χ_i exhibits only a slight decline ($7.65 \text{ m}^2 \text{ s}^{-1}$), but after considering electron collision effects, χ_i significantly reduced to $0.96 \text{ m}^2 \text{ s}^{-1}$. This indicates that ion collision has little effect on ion thermal transport, while electron collision

has significant effects in the high β_p discharge in the EAST. Based on that case, increasing R/L_{Te} within the error range can increase χ_i to $1.1 \text{ m}^2 \text{ s}^{-1}$, which is very close to the experimental value. Electron thermal turbulent transport diffusivity χ_e is also obtained by simulation, as shown in figure 8(b). The dependency of χ_e with collision and R/L_{Te} are similar with that of χ_i . But χ_e is more sensitive to R/L_{Te} , and χ_e only reaches about 30% of the experimental value even if R/L_{Te} is

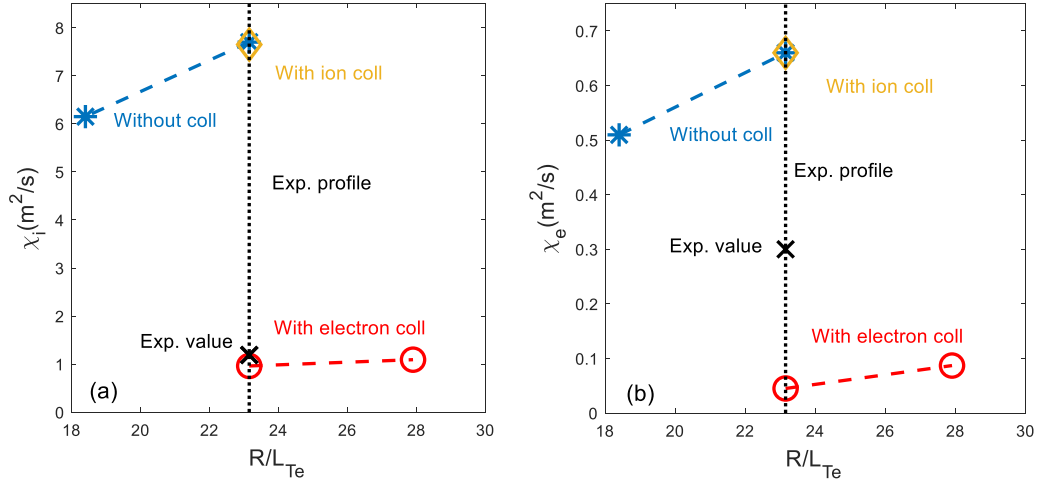


Figure 8. Ion (a) and electron (b) thermal diffusivities given by TRANSP (black cross) and different simulation cases. Blue stars stand for simulations without collision effects, the yellow diamond stands for the simulation with ion collision effects, and red circles stand for simulations with electron collision effects.

Table 2. Ion and electron thermal diffusivities given by gyrokinetic simulations in different cases.

	R/L_{Te}	$\chi_i \text{ (m}^2 \text{ s}^{-1}\text{)}$	$\chi_e \text{ (m}^2 \text{ s}^{-1}\text{)}$
Exp. value (TRANSP)	23.15	1.19	0.30
w/o coll	23.15	7.7	0.66
w/o coll	18.40	6.15	0.51
With ion coll	23.15	7.65	0.66
With electron coll	23.15	0.96	0.045
With electron coll	27.89	1.1	0.087

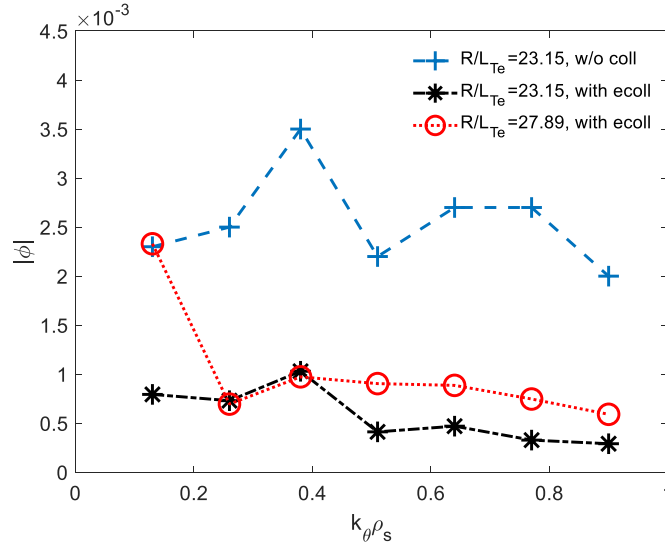


Figure 9. Average values of $|\phi|$ for different $k_\theta \rho_s$ at the last $20 R_0/c_s$ of simulations in different simulation cases.

increased after the addition of electron collision effects. It is proposed that electron-scale turbulence ETG may contribute to the electron thermal transport in high β_p discharge in the EAST. However, electron-scale simulation exceeds our current computational capability, and the related issues will be left to future works.

Figure 9 gives the average values of the amplitude of perturbed potential ($|\phi|$) at $80 \sim 100 R_0/c_s$ of simulations in different situations. It is shown that after adding electron collision effects and keeping the experimental profile fixed, the $|\phi|$ of modes where $k_\theta \rho_s > 0.38$ significantly decline to about 15% of that without collision effects, and the $|\phi|$ of modes

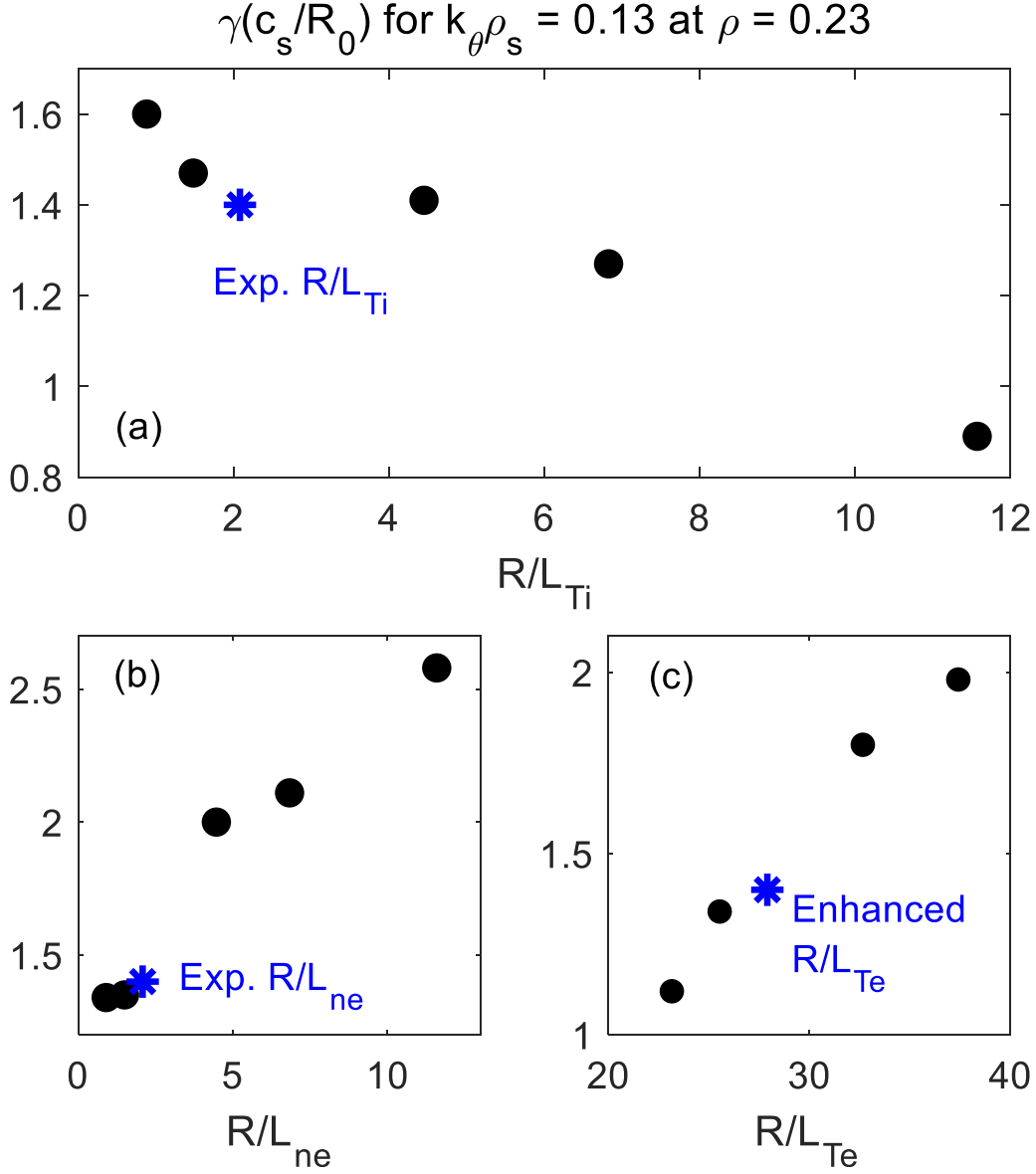


Figure 10. Parametric dependence of linear growth rate of mode with $k_\theta \rho_s = 0.38$ on ion-temperature scale length (a), electron-density scale length (b), and electron-temperature scale length (c). The blue stars indicate simulations performed with experimental Ti, ne profiles, and enhanced R/L_{Te} profile.

where $k_\theta \rho_s < 0.38$ fall to about 30% of that without collision effects. This indicates that electron collision effects exhibit stronger suppression for modes with higher $k_\theta \rho_s$. The $|\phi|$ of modes for $k_\theta \rho_s > 0.38$ doubles after increasing R/L_{Te} , but it is still lower than that without collision effects. The $|\phi|$ of modes for $|\phi|$ change little, the $|\phi|$ of mode where $k_\theta \rho_s = 0.13$ increases to the level without collision effects. In this case ($R/L_{Te} = 27.89$, with ecoll), the mode for $k_\theta \rho_s = 0.13$ dominates the turbulence.

To further investigate the instability in the simulation that χ_i is closest to the experimental value ($R/L_{Te} = 27.89$, with ecoll), a linear scan has been performed. Figure 10 gives the parametric dependence of the linear growth rate γ with the enhanced R/L_{Te} profile. The dependencies of γ with R/L_{Ti} , R/L_{ne} and R/L_{Te} are similar to that in figure 5.

These properties indicate that the dominant instability in this case is still CTEM.

Figure 11 shows the poloidal cross-sections of the normalized potential fluctuation in the nonlinear saturation phases ($99 R_0/c_s$) of two simulation cases ($R/L_{Te} = 23.15$, w/o coll and $R/L_{Te} = 27.89$, with ecoll). It is found that the fluctuations in the bad curvature region are much higher for both cases. This is consistent with the structure of TEM. The typical turbulence eddies with radially elongated structures are formed in figure 10(a). The intensity of turbulence is obviously reduced and the radially elongated structures disappear in figure 10(b). This may infer that electron collision effects reduce the radial correlation length and suppress the turbulence. Another possible reason could be that the collisions weaken the instability so that it could not drive such strong radial flows.

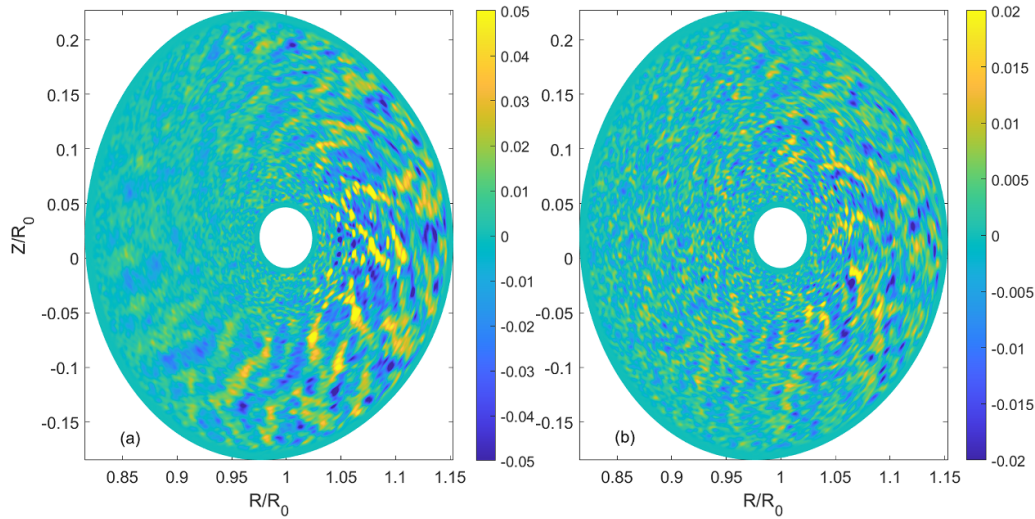


Figure 11. Poloidal cross-sections of the normalized potential fluctuation in different simulation cases. Simulation using experimental profile and without collision effects (a), and simulation using modified profile and with electron collision effects (b).

5. Conclusions and discussions

Recent experiments on the EAST tokamak have achieved high β_p scenarios with high confinement using only RF heating. In this work, gyrokinetic simulations are performed based on experimental data of the typical high- β_p discharge on the EAST to investigate the properties of instabilities and turbulent transport.

Linear simulation results focus on the radial position where R/L_{Te} reaches a maximum value. The turbulence spectrum shows that instability with $k_\theta \rho_s = 0.38$ dominates the turbulence and all ion-scale instabilities propagate in the electron diamagnetic direction. A parameter scan of the dominant instability shows that R/L_{Te} and R/L_{ne} destabilize the turbulence, while R/L_{Ti} slightly reduces the turbulence, the collision effects effectively stabilize the turbulence. These features fit the description of CTEM in previous research. It is also found in the R/L_{Ti} scan that a TEM/ITG hybrid mode exists when R/L_{Ti} exceeds 4, and ITG may dominate over TEM if R/L_{Ti} approaches or exceeds R/L_{Te} .

Nonlinear simulation results show that by modifying the electron temperature profile within the range of experimental error and adding the electron collision effects in the simulation, the ion thermal diffusivity can be made to approach the experimental value given by TRANSP. After adding electron collision effects and modifying the profile, instability with $k_\theta \rho_s = 0.13$ dominates the turbulence and modes with higher $k_\theta \rho_s$ are obviously suppressed. By comparing the poloidal cross-sections of potential fluctuation of two simulation cases, it is found that the intensity of turbulence is obviously reduced and the radially elongated structures disappeared when adding collision effects into the simulation. These analyses imply that the electron collision effects are essential for ion thermal transport in a high β_p discharge on the EAST.

In this work, we mainly focus on the core region where T_e and R/L_{Te} are much higher than T_i and R/L_{Ti} , since the high

T_e/T_i ratio at the core is one of the main characteristics in high β_p discharges using only RF heating on the EAST. The dominant instability could be different at different radial locations, so there may be better agreement with experimental data for χ_e in some other radial regions. The transport-level comparison between different radial regions could be left to future works.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Acknowledgments

This work was supported by the National MCF Energy R&D Program of China under Grant Nos. 2019YFE03060000, 2019YFE03050000 and 2019YFE03020004, National Natural Science Foundation of China (Grant Nos. 11675053, 12005063, and 11875131), Users with Excellence Program of Hefei Science Center CAS, Grant Nos. 2020HSC-UE011 and 2021HSC-UE015, and Anhui Provincial Natural Science Foundation No. 2008085Jo4. Numerical computations were performed on the ShenMa High Performance Computing Cluster in Institute of Plasma Physics, Chinese Academy of Science.

ORCID iDs

S Y Zheng <https://orcid.org/0000-0003-0802-5467>
D B Zhang <https://orcid.org/0000-0001-8965-3611>
E B Xue <https://orcid.org/0000-0003-3864-2140>
L M Yu <https://orcid.org/0000-0003-1994-2818>
Y Xiao <https://orcid.org/0000-0001-5333-2867>
M Q Wu <https://orcid.org/0000-0003-0703-0096>

References

- [1] Cordey J G, Challis C D and Stubberfield P M 1988 *Plasma Phys. Control. Fusion* **30** 1625
- [2] Garofalo A M et al 2014 *Fusion Eng. Des.* **89** 876
- [3] Kamada Y et al 1994 *Nucl. Fusion* **34** 1605
- [4] Politzer P A et al 2005 *Nucl. Fusion* **45** 417
- [5] Garofalo A M et al 2015 *Nucl. Fusion* **55** 123025
- [6] Garofalo A M et al 2018 *Plasma Phys. Control. Fusion* **60** 014043
- [7] McClenaghan J et al 2020 *Nucl. Fusion* **60** 046025
- [8] Huang J et al 2020 *Nucl. Fusion* **60** 126007
- [9] Gong X Z et al 2019 *Nucl. Fusion* **59** 086030
- [10] Wu M Q et al 2019 *Nucl. Fusion* **59** 106009
- [11] Ding S, Jian X, Garofalo A M, Yan Z, McClenaghan J, Guo W and Grierson B A 2020 *Nucl. Fusion* **60** 016023
- [12] Ryter F et al 2019 *Nucl. Fusion* **59** 096052
- [13] Ruiz Ruiz J, Gutfenfelder W, White A E, Howard N T, Candy J, Ren Y, Smith D R, Loureiro N F, Holland C and Domier C W 2020 *Phys. Plasmas* **27** 122505
- [14] Lao L L, St John H, Stambaugh R D, Kellman A G and Pfeiffer W 1985 *Nucl. Fusion* **25** 1611
- [15] Zang Q, Hsieh C L, Zhao J, Chen H and Li F 2013 *Rev. Sci. Instrum.* **84** 093504
- [16] Li Y Y et al 2014 *Rev. Sci. Instrum.* **85** 11E428
- [17] Wang Y M, Gao X, Ling B L, Zhang S B, Zhang T, Han X, Liu S C, Liu Z X, Liu Y and Ti A 2013 *Fusion Eng. Des.* **88** 2950–5
- [18] Qian J et al 2017 *Nucl. Fusion* **57** 036008
- [19] Lin Z, Hahm T S, Lee W W, Tang W M and White R B 1998 *Science* **281** 1835
- [20] Liao X, Lin Z, Holod I, Li B and Sun G Y 2016 *Phys. Plasmas* **23** 122305
- [21] Holod I and Lin Z 2013 *Phys. Plasmas* **20** 032309
- [22] Lin Z, Tang W M and Lee W W 1995 *Phys. Plasmas* **2** 2975
- [23] Zhao C and Xiao Y 2018 *Phys. Plasmas* **25** 102303
- [24] Lin Z, Ethier S and Hahm T S 2002 *Phys. Rev. Lett.* **88** 195004
- [25] Rewoldt G, Lin Z and Idomura Y 2007 *Comput. Phys. Commun.* **177** 775
- [26] Bonanomi N, Mantica P, Szepesi G, Hawkes N, Lerche E, Miglano P, Peeters A, Sozzi C, Tsalas M and van Eester D 2015 *Nucl. Fusion* **55** 113016
- [27] Hawryluk R J 1981 *Physics of Plasma Close to Thermonuclear Conditions* (New York: Pergamon)