Characteristics of electron temperature profile stiffness in electron-heated plasmas on EAST

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Abstract

A very high core electron temperature (T_e0 ∼ 10 keV) plasma has been established and stably sustained by applying both lower hybrid wave (LHW) and on-axis electron cyclotron resonance heating (ECRH) in the Experimental Advanced Superconducting Tokamak (EAST). In this work, power balance analysis shows that the increase of ECRH power can increase the normalized T_e gradient significantly at the plasma core region (ρ < 0.6), but does not change the T_e profile stiffness in the low-density L-mode plasmas. This has been considered to be due to a strong synergistic effect between ECRH and LHW. Furthermore, three distinguishable stages characterized by different T_e profile stiffnesses can be identified from the density ramp-up in the electron-heated plasma on EAST. A stronger T_e profile stiffness at ρ = 0.3 has been observed in the Stage-II, where the LHW power deposition gradually moves away from the plasma core region, following the electron density increases. Furthermore, the formation of an internal plasma density transport barrier inside ρ ∼ 0.6, accompanied by a sudden drop in core T_e and a rise in both core plasma density and ion temperature, has been observed for the first time during the transition from the Stage-II to the Stage-III when the central line-averaged plasma density reaches a threshold of 2.2 × 10¹⁹ m⁻³. This finding strongly affects further development of high-performance gas-fueled electron-heated plasma scenarios in EAST and suggests an advanced operational regime with a wide internal plasma density transport barrier.

Keywords: high core electron temperature, density ramp-up, ECRH, transport, stiffness

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

It is foreseen that the high energy alpha particles created in the deuterium–tritium fusion reaction will give priority to heating electrons and then heat ions through electron–ion collisions [1]. Therefore, the study of electron temperature profiles and heat transport properties for electron heating dominant plasmas is an important research topic and has been extensively explored in many tokamak and stellarator devices [1–9]. On ASDEX Upgrade, the electron heat transport has been investigated in both low-density L-mode plasmas with pure electron heating provided by electron cyclotron resonance heating (ECRH) and ion heated H-mode plasmas sustained by neutral beam injection [6, 10]. The experimental results demonstrated a threshold in the normalized $T_e$ gradient $R/L_{Te}$ above which the turbulent transport increases with $R/L_{Te}$ [11, 12]. On the Large Helical Device, high electron temperature plasmas characterized by formation of an internal electron transport barrier (e-ITB) at the core region have been obtained by applying strongly centrally focused ECRH beams [5, 13]. Recently, ion temperature clamping has also been observed in electron-heated L-mode plasmas on both ASDEX Upgrade and Wendelstein 7-X [14, 15], and it appears to be independent of the magnetic configuration. It could also greatly limit the performance of future fusion devices dominated by electron heating.

The Experimental Advanced Superconducting Tokamak (EAST) is an electron heating dominated tokamak device, which is designed to achieve long-pulse steady-state high-performance H-mode plasmas in ITER-like divertor configurations and radio frequency (RF) wave heating schemes [16–18]. Two main categories of micro-instabilities, trapped electron modes (TEM) and electron temperature gradient (ETG) driven modes, have been identified as the dominant mechanism to drive the turbulent transport in pure RF waves heating plasmas on EAST. In previous experiments, a significant degradation in plasma performance after ECRH termination was observed in electron heating dominant H-mode discharges. Further transport analysis demonstrated the importance of synergistic effects between LHW and ECRH for the development of the advanced scenarios, especially for the e-ITB formation [19]. The analysis of $T_e$ profile stiffness would support the exploration of stiffness breaking in electron heating dominant tokamaks [20], such as EAST and, in future, ITER.

Recently, EAST has been upgraded with installation of two new ECRH systems, and can establish a stable long-pulse operation scenario with very high core electron temperature ($T_{eo} \sim 10$ keV). Core MHD instabilities and modeling very high electron heating in such a scenario have been reported [21, 22]. Such a scenario also provides a good platform for characterizing the $T_e$ profile stiffness and plasma transport in electron-heated plasmas. Previous results have demonstrated that the strong synergistic effect between on-axis ECRH and LHW can effectively increase the core $T_e$ on EAST [19, 21]. This work is focused on the stiff turbulent transport analysis with a high core $T_e$ and, furthermore, its density dependence in electron-heated plasmas. The first observation of formation of an internal plasma density transport barrier inside $\rho \sim 0.6$, accompanied by a sudden drop in core $T_e$ and a rise in both core density and ion temperature, will be presented.

The rest of this paper is organized as follows: the analysis of electron temperature profile stiffness in very high $T_{eo}$ plasmas is discussed in section 2. The characteristics of the electron temperature profile stiffness with a ramp-up in electron density are shown in section 3. Finally, the discussion and conclusion are presented in section 4.

2. Characteristics of electron temperature profile stiffness in very high $T_{eo}$ plasmas

On EAST, a very high central electron temperature of about 10 keV has been achieved and stably maintained in electron-heated plasmas by applying a 4.6 GHz LHW simultaneously with two on-axis power deposited ECRHs. Figure 1 shows an overview of the main plasma parameters from this experiment. At the plasma flat top, the toroidal current $I_p$ is 0.45 MA, the magnetic field $B_{T0}$ is 2.42 T, and the central line averaged electron density $\langle n_e \rangle$ is stably feedback controlled at $1.8 \times 10^{19}$ m$^{-3}$. In order to achieve a very high central electron temperature and a larger electron-to-ion temperature ratio, a low-density L-mode plasma was selected for operation. The total plasma heating power is about 2.6 MW, including $P_{LHW} = 1.8$ MW, $P_{ECRH} = 0.4$ MW and $P_{ECRH} = 0.4$ MW. The loop voltage was well controlled to be zero during the
Figure 2. (a) Electron temperature profiles, (b) ion temperature profile, (c) electron density profiles and (d) experimental normalized $T_e$ gradient $R/L_{Te}$ vs time at different normalized radius $\rho$.

Figure 3. (a) The LHW power deposition density profile, (b) the total RF (LHW + ECRH) current density of EAST #78841.

plasma flat top, indicating that a fully non-inductive plasma current was achieved. Compared with the single ECRH heating stage, the central electron temperature increases significantly with the second ECRH injection at $t = 3.1$ s. The electron temperature ratio between plasma core ($\rho = 0$) and larger radius ($\rho = 0.8$), $T_{e0}/T_{e0.8}$, increases significantly after the
second ECRH injection, and it is by a factor of 2 larger than that with LHW heating only. It should be noted that the ion temperature \(T_i\) in the plasma flat-top remains \(T_{i0} < 1\) keV, and the temperature ratio of ion to electron, \(T_i/T_e\), is below 0.1 at the plasma core. Additionally, the stored energy \(W_{\text{mhd}}\) and internal inductance \(l_i\) increase correspondingly with ECRH injection. It should be noted that the internal inductance \(l_i\) increases slowly after the second ECRH injection, which indicates that the plasma is not completely steady-state during this period.

Figure 2 shows the kinetic profiles measured at three different heating phases with (i) only LHW, (ii) LHW and one on-axis ECRH and (iii) LHW and two on-axis ECRHs, respectively, and the time evolution of the normalized radial profiles of \(R/L_{Te}\) [23, 24]. The time points of three different phases are shown in figure 2(d). Core \(T_e\) (measured by the Thomson scattering (TS) diagnostic [25]) increases visibly with on-axis ECRH injection. The normalized \(T_e\) gradient \(R/L_{Te}\) increases by about 50% at \(\rho \sim 0.2–0.4\), and the core \(T_e\) profile becomes rather peaked after beginning the second on-axis ECRH injection. The \(T_e\) in the boundary region (\(\rho \gtrsim 0.6\)) stays nearly constant during this process. Here, the \(T_i\) profiles are constant during the RF heating phase which measured by the charge-exchange recombination spectroscopy. The electron density \(n_e\) profile becomes flat with the increase of ECRH power, which was reconstructed using measurements of the 11-channel far infrared laser polarimeter-interferometer (POINT) diagnostic [26].

The ray-tracing codes GENRAY, TORAY and Fokker–Planck code CQL3D were used to calculate the heating and current drive by LHW and ECRH. Figure 3 shows the LHW heating power density and the total RF (LHW + ECRH) current density during the different heating phases. Both the LHW power density and the total RF current density gradually peak with on-axis ECRH injection, which indicates a strong synergistic effect between ECRH and LHW on EAST. A detailed analysis of heating and driven current can be found in a dedicated manuscript [21]. On-axis ECRH power injection causes an obvious increase in the core LHW power density profile [19, 27]. The LHW power deposition density has no obvious response to the second ECRH injection at 3.1 s, while the total RF current density in the core increases significantly. This indicates that the realization of high core electron temperatures is closely related to a strong synergistic effect between on-axis ECRH and LHW in a lower density plasma.

The stiffness of the electron temperature profile from power balance was analyzed for the high \(T_{e0}\) plasmas by using transport code TRANSP [28] combined with the equilibrium code kinetic-EFIT [29, 30]. The profile stiffness \(S^*\) is defined by:

\[
S^* = \frac{\partial q_{\text{GB}}^e}{\partial R/L_{Te}}.
\]
Figure 7. Time evolution of (a) plasma current $I_p$ and loop voltage, (b) auxiliary heating power of LHW and ECRH, (c) line averaged density, (d) core $T_e$ measured by ECE diagnostic and core $T_i$ measured by tangential imaging XCS diagnostic, (e) stored energy ($W_{\text{st}}$) and energy confinement enhancement factor ($H_{98}$), (f) internal inductance $l_i$ and (g) frequency spectrums of soft x-ray perturbations for EAST #103200.

Here, the electron heat flux (in gyro-Bohm units) is defined as $q_{eGB} = q_eBR_e^2/nT_e^2\rho_s$, where $\rho_s$ is Larmor radius, $R$ is the plasma major radius, $T_e$ is the electron temperature, $n$ is the electron density, and $B$ is the toroidal magnetic field. Both the electron heat flux and the driving gradient for the flux are normalized to be dimensionless quantities [11, 31, 32] rather than absolute quantities, especially to facilitate comparison with theory and models. By convention, we chose to normalize the gradient of a fluid property against the major radius of the flux surface, e.g. $R/L_{Te} = R\nabla T_e \cdot \hat{r}/T_e$.

Figure 4 shows the relationship between the normalized $T_e$ gradient $R/L_{Te}$ and the electron heat flux in gyro-Bohm units ($q_{eGB}$) in different flux surfaces. The three different heating phases are represented by different symbols. Since the internal inductance $l_i$ has been increasing during the flat-top phase, the evolution of electron heat flux $q_{eGB}$ and $R/L_{Te}$ is calculated based on the experimental kinetic profiles with a time interval of 0.2 s (TS sampling rate). Here, the dashed line represents the guide of sight based on the statistical interval, which yield the slope to represent the $T_e$ profile stiffness ($S^*$). The results show that the increase of ECRH power can increase the normalized $T_e$ gradient significantly in the plasma core region ($\rho<0.4$), but does not change the $T_e$ profile stiffness. Qualitatively, the electron heat flux $q_{eGB}$ does not increase dramatically with the increase of normalized $T_e$ gradient $R/L_{Te}$ inside $\rho<0.4$. This indicates that the $T_e$ profile stiffness is extremely weak or potentially even broken inside $\rho<0.4$. Power balance analysis
also shows that the $T_e$ profile stiffness gradually becomes stronger as the normalized radius $\rho$ moves away from the plasma core region.

Figure 5 shows the results of power balance analyses for the effective electron thermal diffusivity $\chi_e$ (defined as $\chi_e = q_e/n_e \nabla T_e$, where the electron heat flux $q_e$ is calculated from electron heat balance equation [33]) at different time slices. The effective electron thermal diffusivity $\chi_e$ is low at both time slices in the core, but increases significantly at $\rho \sim 0.6$ with the second on-axis ECRH injection. Here, the TGLF [34, 35] (pulled from the GitHub repository on May 23rd, 2019 [36]) with SAT0 is used to compute the spectrum of the most unstable linear eigenmodes. This spectrum is used to construct quasi-linear turbulent transport fluxes with their saturation scaling determined by calibrating to GYRO [37] non-linear simulations. The growth rate and frequency spectrum of the most unstable modes at $\gamma \sim 0.6$ with SAT0 is used to compute the spectrum of the most unstable linear eigenmodes. This spectrum shows that the growth rate of the low- $k$ modes gradually decreases as the normalized radius $\rho$ moves outward.

The effective electron thermal diffusivity $\chi_e$ is low at both time slices in the core, but increases significantly at $\rho \sim 0.6$ with the second on-axis ECRH injection. Here, the TGLF [34, 35] (pulled from the GitHub repository on May 23rd, 2019 [36]) with SAT0 is used to compute the spectrum of the most unstable linear eigenmodes. This spectrum is used to construct quasi-linear turbulent transport fluxes with their saturation scaling determined by calibrating to GYRO [37] non-linear simulations. The growth rate and frequency spectrum of the most unstable modes at $\rho = 0.4$ and $\rho = 0.6$ are shown in figure 6. The system of units used is $c_s = \sqrt{T_e/m_e}$, $\rho_e = c_s/\Omega_e$, $\Omega_e = eB/m_ec$. The normalized growth rate, frequency, and poloidal wave number are $\gamma' = \gamma/a(c_s)$, $\omega' = \omega/a(c_s)$, $k_y = \rho_e k_0$, respectively, where $a$ is the plasma minor radius. A positive sign of $\omega'$ indicates a mode rotating in the electron diamagnetic direction. From the growth rate and frequency calculated by TGLF, we can find that the most unstable modes are the medium wavelength low-$k (k_y < 1)$ TEMs. As shown in figure 6, the normalized growth rate of the low-$k (k_y < 1)$ TEMs increased slightly after beginning the second ECRH injection at $\rho = 0.4$, which is mainly responsible for driving the electron energy flux [27]. This is consistent with the peaked $T_e$ profile, because the low-$k (k_y < 1)$ TEM is mainly driven by $T_e$ and $n_e$ gradients [32]. The results also show that the growth rate of the most unstable modes gradually decreases as the normalized radius $\rho$ moves outward.

3. Characteristics of electron temperature profile stiffness with electron density ramp-up

In addition to the experiment presented in section 2, a slow density ramp-up caused by gas puffing was also performed in a high core $T_e$ low-density L-mode plasma on EAST. In this experiment, the target plasma was sustained by 1.6 MW LHW at 4.6 GHz and three on-axis ECRH injections with a total power of 1.25 MW. The time evolution of major plasma parameters of this discharge are shown in figure 7. During the plasma current plateau ($I_p = 0.55$ MA) over 6 s, the loop voltage is almost zero, the toroidal magnetic field is fixed at $B_T = 2.4$ T, and the central line averaged electron density has a slow ramp-up from $1.5 \times 10^{19}$ m$^{-3}$ to $3.3 \times 10^{19}$ m$^{-3}$. Due to the collisional coupling effect between electrons and ions, the core $T_e$ measured by the tangential imaging x-ray crystal spectrometer (XCS) [38, 39] increases with the rising $n_e$, while the core $T_e$ measured by electron cyclotron emission (ECE) diagnostic (the black line shown in figure 7(d)) drops. There are two sudden drops in the core $T_e$ occurring at $t = 3.5$ s, and $t = 6$ s, respectively. Both the central line averaged density $\langle n_e \rangle$ and the core $T_e$ substantially increased after $t = 6$ s, associated with a significant reduction in the core $T_e$. Furthermore, three distinguishable stages characterized by different $T_e$ profile stiffnesses can be identified from the density ramp-up, divided into a first stage (Stage-I: 2.5 s−3.5 s), a second stage (Stage-II: 3.5 s−6 s) and a third stage (Stage-III: 6 s−9 s), respectively. An overview of MHD activity is illustrated in the figure 7(g) by showing the time frequency spectra of soft x-ray radiation. The dominant MHD activities consist of sawtooth modes and sawtooth precursors, with varying mode amplitude and mode number $m = 1$, $n = 1$. The frequency of MHD activities decreases gradually with density ramp-up. Since those MHD activities are relatively stable in different phases, they do not affect the trend of $T_e$ profile stiffness. The stored energy ($W_{\text{mhd}}$) and the energy confinement enhancement factor ($H_{90}$) increase significantly following the density ramp-up, with $W_{\text{mhd}}$ increasing by a factor 2 in third stage compared to the first stage. When increasing the electron density, an increase of the collisional coupling effect between electrons and ions enhances the central ion pressure (estimated as $n_e^2 T_{e0}$ and shown in figure 8), which has a similar trend as the stored energy. In addition, the plasma internal inductance $l_i$ also responds to the density changes. The corresponding dynamic analysis in current distribution is shown in figure 9(a). ECRH current density is reduced with rising $n_e$, and LHW current density peak moves away from the plasma core range during this process. As a result, the synergistic effect between LHW and ECRH in the plasma core range becomes weaker with increasing $n_e$. This is consistent with the trend of the decreasing internal inductance $l_i$ shown in the main plasma parameters. Figure 9(b) shows the profile of safety factor ($q$), which increases slightly following the density ramp-up.

Figures 10(a)–(c) show the radial profiles of $T_e$, $T_i$ and $n_e$ measured from these three different stages. By comparing the first and second stage, it is clear that not only the value of the core $T_e$ decreases, but also the gradient of the core $T_e$ profile decreases as $n_e$ increases. At the same time, the plasma density increases overall, but its profile shape changes less.
Figure 9. (a) LHW and ECRH current density profile and (b) safety factor profile of EAST shot #103200.

Figure 10. (a) Electron temperature profile, (b) ion temperature profile, (c) electron density profile and (d) the relative variations between $T_{ii}/T_{ei}$ ratio and line averaged density $\langle n_e \rangle$ for EAST shot #103200.
Here, the $n_e$ profile was reconstructed using measurements of the 11-channel far infrared laser POINT diagnostic. Furthermore, a steep density gradient appears inside $\rho \sim 0.6$ when the central line-averaged plasma density reaches a threshold $2.2 \times 10^{19} \text{ m}^{-3}$ at $t = 6 \text{ s}$, and is stably sustained during the third stage as shown in figures 7(c) and 10(c). The $T_i$ profile measured in the third stage has a significant overall rise comparing with that observed in the previous two stages. As shown in figure 10(d), the ratio of $T_i/\langle n_e \rangle$ increases from 0.06 to 0.19 by a factor of 3 with the increase of the line averaged plasma density $\langle n_e \rangle$ from $1.5 \times 10^{19} \text{ m}^{-3}$ to $3.3 \times 10^{19} \text{ m}^{-3}$.

Significant differences in the radial profiles of the normalized $T_e$ gradient $R/L_{Te}$, and the normalized electron density gradient $R/L_{ne}$, are also observed in the above three stages. In the first stage, $R/L_{Te}$ has a large value in the core region ($\rho = 0.2–0.3$), while a clear density internal transport barrier appears inside $\rho \sim 0.6$ in the third stage, where $R/L_{Te}$ is decreased clearly compared to the first stage. The density internal transport barrier is stably sustained even with a higher plasma density of $3.3 \times 10^{19} \text{ m}^{-3}$. Figure 11(c) shows the variation of $R/L_{ne}$ with the line averaged density $\langle n_e \rangle$. The $R/L_{ne}$ increases rapidly after the central line-averaged plasma density reaches a threshold of $2.2 \times 10^{19} \text{ m}^{-3}$, and the $R/L_{ne}$ increases more slowly at $\rho = 0.4$ than at $\rho = 0.6$. Figure 12(a) shows the variation of electron heat flux $q_e^{GB}$ (in gyroBohm units) with the line averaged density $\langle n_e \rangle$. The electron heat flux $q_e^{GB}$ at $\rho = 0.3$ remains stable when the central line-averaged plasma density exceeds a threshold of $2.2 \times 10^{19} \text{ m}^{-3}$, which is strongly related to the current density distribution (as shown in figure 9(a)). Figure 12(b) shows the time evolution of particle flux ($\Gamma_p$) and pinch velocity ($V_p$) at different normalized
radius $\rho$. Quantitatively, the particle flux gradually increases as the density climbs. However, the increase in particle flux becomes larger in the third stage as the normalized radius $\rho$ moves outward, while the pinch velocity decreases gradually in this process. This result is consistent with the formation of a density internal transport barrier.

Figure 13 shows the time traces of electron temperature profile stiffness at $\rho = 0.3$. Compared to the experiment discharge discussed in section 2 (EAST SN#78841), three distinguishable stages, characterized with different $T_e$ profile stiffness as the density ramp-up can be observed. The key parameters of #78841 and #103200 are summarized in table 1. The reason for the changes of electron temperature profile stiffness as the density ramp-up will be discussed in detail.

In Stage-I (2.5 s–3.5 s), the core $T_e$ gradient drops significantly with the $n_e$ climbing at $\rho = 0.3$, as shown by the red dotted line in the figure 13. In comparison, the drop of electron heat flux is small, where the slope indicates a much weaker $T_e$ profile stiffness. Figure 14 shows the transport coefficients of effective electron thermal diffusivity ($\chi_e$) and particle diffusivity ($D_{\text{eff}}$) calculated by power balance analyses, which indicates that the plasma confinement performance in the first stage is not better than the other two stages. The peaked core electron temperature profile in the first stage is mainly related to the high electron heat flux. The most unstable modes at $\rho = 0.3$ are low-$k$ ($k_e < 1$) TEM modes (as shown in figure 15), whose growth rate reduces visibly with increasing density. This result is consistent with the drops in the core $T_e$ gradient and the effective electron thermal diffusivity $\chi_e$.

In Stage-II (3.5 s–6 s), a strong $T_e$ profile stiffness can be found at $\rho = 0.3$. As the green dashed line shown in figure 13, the electron heat flux $q_{\text{GB}}^e$ drops significantly following the density ramp-up, while the core $T_e$ gradient remains almost unchanged. This indicates that the change of electron heat flux does not alter the normalized $T_e$ gradient under the strong $T_e$ profile stiffness. Corresponding to the most unstable modes, we can find the low-$k$ ($k_e < 1$) TEM modes gradually increasing in the second stage, while the core effective electron thermal diffusivity $\chi_e$ keeps flat in the core range.

In Stage-III (6 s–9 s), the $T_0/T_0^0$ ratio becomes more larger as $n_e$ climbs, while the $T_e$ profile stiffness stays weak with a slope is similar to the first stage, as shown in figure 13 (blue dashed line). The third stage has the weakest $T_e$ profile stiffness out of all stages. Furthermore, the formation of a density internal transport barrier inside $\rho \sim 0.6$ after 6 s (which can be seen from figures 10(c) and 11(b)), accompanied by a sudden drop in core $T_e$ and a rise in both core $n_e$ and $T_i$ (the core $T_i$ increased by 20%), is being observed for the first time during the transition from the second stage to the third stage when the central line-averaged plasma density reaches a threshold of $2.2 \times 10^{19}$ m$^{-3}$. Additionally, the core particle diffusivity decreases in the third stage (as shown in figure 14), which also indicates the formation of a density internal transport barrier.
Table 1. Comparison between high \(T_e\) discharge (EAST\#78841) and density ramp-up discharge (EAST\#103200).

| Cases          | \(R/\ell_{Te}\) | \(R/\ell_{Tn}\) | \(T_e/T_i\) | \(q\)  | \(\psi^a\) | \(\psi^b\) | \(\beta_p\) | \(\beta_n\) | \(Z_{eff}\) |
|----------------|-----------------|-----------------|-------------|------|-----------|-----------|-----------|-----------|-----------|
| 78841@2.9 s (\(\rho = 0.4\)) | 9.56            | 1.55            | 3.45        | 1.45 | 0.94      | 0.16      | 0.68      | 0.62      | 3.1       |
| 78841@2.9 s (\(\rho = 0.6\)) | 7.41            | 2.56            | 2.40        | 2.43 | 1.77      | 0.25      | 0.68      | 0.62      | 3.1       |
| 78841@3.3 s (\(\rho = 0.4\)) | 12.38           | 1.55            | 3.63        | 1.39 | 0.96      | 0.14      | 0.79      | 0.72      | 3.9       |
| 78841@3.3 s (\(\rho = 0.6\)) | 6.45            | 2.56            | 2.21        | 2.42 | 1.87      | 0.24      | 0.79      | 0.72      | 3.9       |
| 103200@3.0 s (\(\rho = 0.3\)) | 9.81            | 1.41            | 7.54        | 0.81 | 0.58      | 0.21      | 0.53      | 0.57      | 3.8       |
| 103200@5.5 s (\(\rho = 0.3\)) | 8.68            | 2.10            | 6.01        | 0.87 | 0.48      | 0.13      | 0.80      | 0.84      | 2.5       |
| 103200@6.5 s (\(\rho = 0.3\)) | 7.49            | 1.69            | 3.66        | 0.93 | 0.51      | 0.14      | 1.01      | 1.04      | 2.0       |

\(^{a}\)s and \(\psi\) are the magnetic shear and collisional frequency, respectively.

Figure 14. Transport coefficients of (a) effective electron thermal diffusivity (\(\chi_{Te}\)) and (b) particle diffusivity (\(D_{eff}\)) calculated by power balance analyses.

Figure 15. The normalized growth rate (a) and frequency spectrum (b) at \(\rho = 0.3\).
barrier. Power balance analysis shows no deterioration in the overall plasma confinement performance in the third stage, which is consistent with the signal of stored energy \((H_{\text{st}})\). For turbulent transport, the growth rate of the most unstable modes is also large at \(\rho = 0.3\), where the density gradient increases after the formation of the density internal transport barrier.

4. Discussion and conclusion

The stiff transport in high \(T_e\) and density ramp-up experiments on EAST have been described above. A strong synergistic effect between LHW and ECRH was observed, however, the present experimental results indicate that this effect does not change the electron temperature profile stiffness in the low-density \((n_e \sim 1.8 \times 10^{19} \text{ m}^{-3})\) L-mode plasmas on EAST as shown in figure 4. Furthermore, an increase of the stored energy by a factor of two with the ramp-up of electron density from \(1.5 \times 10^{19} \text{ m}^{-3}\) to \(3.3 \times 10^{19} \text{ m}^{-3}\) was observed. This has been considered to be due to the formation of a density internal transport barrier inside \(\rho \sim 0.6\). At the same time, the central ion pressure, \(n_i^e T_{i0}\), increases by a factor of \(\sim 4\) with the density ramp-up, while the central electron pressure, \(n_e^e T_{e0}\), does not change much, even increases slightly. The underlying cause might be the variation of the current density distribution during the process of increasing density. The LHW current density peak moves away from the plasma core range with rising \(n_e\), which flattens the total current density distribution (the internal inductance \(l_i\) decreases gradually during this process as shown in figure 7(f)), thereby improving the plasma confinement. Although the increase in density affects the propagation of LHW in the plasma, it is beneficial to improve the plasma confinement performance with an optimized plasma density (such as the Stage III in figures 7(e) and 8). The findings in this study support the exploration of the electron-heated high-temperature and high-density plasma operation, which is relevant for the scenario development for future fusion reactors.

The most unstable modes calculated by TGLF in this work are TEMs, which is consistent with the results calculated by using gyrokinetic numerical Lie transform code [40]. Moreover, the reason for the absence of ITG modes might be the small ion temperature gradient in the low-density electron-heated plasmas.

To conclude, a very high core electron temperature \((T_{e0} \sim 10 \text{ keV})\) LHW plasma has been achieved by applying a 4.6 GHz LHW with two on-axis power deposited ECRHs in the 2018 EAST experimental campaign. The core \(T_e\) profile peaked significantly after beginning the second on-axis ECRH injection. The ratio of \(T_{e0}/T_{e0,\text{as}}\) was found to increase substantially, taking a value about twice as large as with LHW heating only. Furthermore, the dependence of electron heat flux \((q_{e0}^{GB})\) on the normalized \(T_e\) gradient \(R/L_{Te}\) was investigated, which yields the slope of dashed line representing the profile stiffness. As a result, due to the strong synergistic effect between on-axis ECRH and LHW, the injection of on-axis ECRH power can increase the normalized \(T_e\) gradient significantly at the plasma core region \((\rho < 0.4)\), but does not change the \(T_e\) profile stiffness. Qualitatively, the \(T_e\) profile stiffness becomes weak as the normalized radius \(\rho\) moves toward to the plasma core region.

Furthermore, a slow density ramp-up from \(1.5 \times 10^{19} \text{ m}^{-3}\) to \(3.3 \times 10^{19} \text{ m}^{-3}\) has been performed in the target plasma dominated by LHW and ECRH synergistic electron heating on EAST. Compared to the previously presented results (EAST SN878841), three distinguishable stages, characterized with different \(T_e\) profile stiffness following the climbing \(n_e\) can be observed. Due to the normalized \(T_e\) gradient \(R/L_{Te}\), decreases rapidly following the reducing electron heat flux \((q_{e0}^{GB})\), the \(T_e\) profile stiffness at \(\rho = 0.3\) is relatively weak in the first stage. The drop of the low-\(k(k_0 < 1)\) TEM modes is consistent with the decrease of the core \(T_e\) gradient.

A strong \(T_e\) profile stiffness at \(\rho = 0.3\) can be observed in the second stage, where the core \(T_e\) gradient does not change significantly with the increasing \(n_e\). Current analysis shows that the LHW power deposition moves away from the plasma core region with the rising \(n_e\).

In the third stage, the \(T_e\) profile stiffness becomes much weaker than the other stages. Furthermore, a density internal transport barrier appears inside \(\rho \sim 0.6\) after 6 s, accompanied by a sudden drop in core \(T_e\) and a rise in both core \(n_e\) and \(T_i\) (the core \(T_i\) increased by 20%), being observed for the first time during the transition from the second stage to the third stage when the central line-averaged plasma density reaches a threshold of \(2.2 \times 10^{19} \text{ m}^{-3}\). It also turns out that the density internal transport barrier inside \(\rho \sim 0.6\) can be stably sustained even with a higher plasma density of \(3.3 \times 10^{19} \text{ m}^{-3}\).

The study on \(T_e\) profile stiffness would support the exploration of breaking stiffness in electron heating dominant plasmas on EAST and future ITER.

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References

[1] Ryter F. et al 2006 Plasma Phys. Control. Fusion 48 B453–63
[2] Ryter F. et al 2011 Nucl. Fusion 51 113016
[3] Stallard B.W. et al 1999 Phys. Plasmas 6 1978–84
[4] Viezzer E. et al 2011 Nucl. Fusion 51 113016
[5] Stallard B.W. et al 1999 Phys. Plasmas 6 1978–84
[6] Manini A. et al 2004 Plasma Phys. Control. Fusion 46 1723–43
[7] Shimozuma T. et al 2005 Nucl. Fusion 45 1396–403
[8] Smith S.P. et al 2004 Phys. Plasmas 11 1978–84
[9] Viezzer E. et al 2017 Nucl. Fusion 57 022020
[10] Ida K. et al 2003 Phys. Rev. Lett. 91 085003
[11] Ryter F., Imbeaux F., Leuterer F., Fahrbach H.-U. and Suttrop W. (ASDEX Upgrade Team) 2001 Phys. Rev. Lett. 86 5498–501
[12] Mantica P. et al 2009 Phys. Rev. Lett. 102 175002
[13] Takahashi H. et al 2014 Phys. Plasmas 21 061506
[14] Beurskens M.N.A. et al 2021 Nucl. Fusion 62 016015
[15] Beurskens M.N.A. et al 2021 Nucl. Fusion 61 116072
[16] Li J. and Wan B. 2011 Nucl. Fusion 51 094007
[17] Wan B. 2009 Nucl. Fusion 49 104011
[18] Wan B.N. et al 2017 Nucl. Fusion 57 102019
[19] Du H.F. et al 2018 Nucl. Fusion 58 066011
[20] Sommer F. et al 2015 Nucl. Fusion 55 033006
[21] Huang Y. et al 2021 Nucl. Fusion 61 096026
[22] Xu L. et al 2020 Nucl. Fusion 60 086013
[23] Krommes J.A. 2002 Phys. Rep. 360 1–352
[24] Petty C.C., Wade M.R., Kinsey J.E., Baker D.R. and Luce T.C. 2002 Phys. Plasmas 9 128–36
[25] Qing Z., Junyu Z., Li Y., Qingsheng H., Yanqing J., Tao Z., Xiaoqi X., Bhatti S.H. and Xiang G. 2010 Plasma Sci. Technol. 12 144–8
[26] Liu H.Q. et al 2016 Rev. Sci. Instrum. 87 11D903
[27] Wu M.Q. et al 2019 Nucl. Fusion 59 106009
[28] Hawryluk R. 1981 An empirical approach to tokamak transport Physics of Plasmas Close to Thermonuclear Conditions (Amsterdam: Elsevier) pp 19–46
[29] Lao L.L., Ferron J.R., Groebner R.J., Howl W., St. John H., Strait E.J. and Taylor T.S. 1990 Nucl. Fusion 30 1035–49
[30] Qian J.P. et al 2017 Nucl. Fusion 57 036008
[31] Luce T.C. et al 2018 Nucl. Fusion 58 026023
[32] Wolf R.C. 2002 Plasma Phys. Control. Fusion 45 R1–R91
[33] Braginskii S.I. 1965 Rev. Plasma Phys. 1 205
[34] Staebler G.M., Kinsey J.E. and Waltz R.E. 2005 Phys. Plasmas 12 102508
[35] Staebler G.M., Kinsey J.E. and Waltz R.E. 2007 Phys. Plasmas 14 055909
[36] Chen J. et al 2021 Nucl. Fusion 61 046002
[37] Candy J. and Waltz R.E. 2003 J. Comput. Phys. 186 545–81
[38] Wang F. et al 2016 Rev. Sci. Instrum. 87 11E342
[39] Wang F. et al 2011 J. Korean Phys. Soc. 59 2734–8
[40] Ye L. et al 2018 Plasma Sci. Technol. 20 074008