PARTICLE TRANSPORT OF OHMIC DISCHARGES WITH DIFFERENT PLASMA CURRENT IN EAST TOKAMAK

S.X. WANG
Institute of Plasma Physics, Chinese Academy of Sciences
Anhui Hefei, China
Email: wangshouxin@ipp.ac.cn

H. Q. LIU, P.J. SUN, G.S. LI, Y.X. JIE, H. LIAN, Y.F JIN, Y.D. YU, Y.Q. CHU
Institute of Plasma Physics, Chinese Academy of Sciences
Anhui Hefei, China

Abstract

Systematic density modulation experiments on EAST tokamak reveal that increasing plasma current significantly reduces particle transport coefficients while maintaining the same line-averaged density. This study investigates the underlying mechanisms of current-dependent particle transport in Ohmic plasmas through density modulation experiments conducted on the EAST tokamak. Under carefully controlled conditions (fixed line-averaged density $\bar{n}_e \approx 2.0\times10^{19}$ m^{-3}, toroidal field B_t = 2.2 T, and identical magnetic configuration), three distinct plasma current levels (I_p = 300 kA, 400 kA, 500 kA) were systematically compared. Experimental results reveal that higher plasma currents lead to elevated electron temperatures (T_e increases by ~25% at ρ = 0) and improved global energy confinement, despite higher plasma current has slightly lower density gradient. To resolve the paradoxical observation of lower plasma current with higher central density peaking, a novel methodology combining experimental analysis and multi-scale simulations was developed. The BOUT++ framework was employed to model particle sources localized at ρ ~ 0.9, aligning with the modulation phase minimum. Through Genetic Algorithm-based (GA) transport coefficient analysis, it was found that both diffusion coefficient and inward convection velocity decrease significantly with increasing plasma current at the plasma edge. The derived transport coefficients exceed neoclassical predictions by 1-2 orders of magnitude, unequivocally demonstrating turbulence-dominated transport dynamics. Further TGLF simulations identify Trapped-Electron Modes (TEM) as the primary turbulence driver, with linear growth rates inversely correlated to plasma current. This current-induced suppression of TEM instability provides a unified explanation for the observed reduction in transport coefficients and enhanced confinement at higher current.

1. INTRODUCTION

The quest for controlled thermonuclear fusion as a sustainable energy source has been a central goal of plasma physics research for decades. Magnetic confinement fusion (MCF) devices, most notably the tokamak, aim to confine high-temperature, high-density plasma long enough for fusion reactions to occur. The performance of such devices is fundamentally governed by transport processes, which determine the loss rates of energy and particles from the plasma core. While significant progress has been made in understanding and controlling energy transport, particle transport remains a critical and less well-understood factor. It directly influences the density profile, which is a key determinant of fusion power output (scaling with n^2) and plasma stability. Therefore, elucidating the mechanisms that govern particle transport is essential for predicting and optimizing the performance of future fusion reactors like ITER and DEMO.

In tokamaks, particle transport is known to be predominantly anomalous, driven by microturbulence rather than classical collisions [1,2,3]. Ohmic discharges provide an ideal testbed for isolating and studying these fundamental processes, as they are free from the complicating effects of additional heating systems such as neutral beam injection (NBI) or radiofrequency (RF) waves, which can introduce fast ions and non-thermal particle sources. A well-established empirical observation is that energy confinement improves with increasing plasma current. This is theoretically attributed to the enhancement of magnetic shear, which suppresses turbulent eddies, thereby reducing turbulent transport.

While this scaling is robust for energy confinement, the response of particle transport to plasma current is more nuanced and less comprehensively documented. In particular, the evolution of the density profile-specifically its peaking-results from a complex interplay between turbulent diffusion, convective pinches (e.g., thermo-diffusion, turbulence-driven pinches), and the source distribution of fuelled particles [4]. The key question remains: how do the fundamental particle transport coefficients, the diffusion coefficient (D) and the convective velocity (V), evolve with plasma current in the absence of auxiliary heating? Resolving this question is crucial for developing validated predictive models of density profiles in reactor-grade plasmas.

In this report, we present a systematic experimental investigation into the dependence of particle transport on plasma current under purely Ohmic conditions. The study was conducted on the EAST tokamak. We employed the active modulation technique of periodic gas puffing, coupled with advanced interferometer and/or reflectometer diagnostics, to perturb the electron density and measure the plasma's response. This powerful technique allows for the direct and localized quantification of the particle transport coefficients, D_{mod} and V_{mod}, across different radial positions. The experiments were performed across a series of stable plasma current platforms, ranging from 300 kA to 500 kA, while maintaining a constant line-averaged density of 2×10^{19} m^{-3}. This design allows us to isolate the effect of current on transport by minimizing the confounding influence of density variations.

Our results confirm the overarching theory that increased plasma current leads to the suppression of turbulent transport, manifesting as a clear reduction in both the particle diffusion and convection coefficients across the plasma radius. However, a more intriguing and novel finding is that despite this overall reduction in transport coefficients, the peaking of the core density profile is observed to decrease at higher currents. This suggests that other current-dependent factors, such as a shift in the ionization source location or an alteration of pinch mechanisms, may become dominant in governing density profile evolution at higher performance levels. This study provides benchmark-quality experimental data on the scaling of particle transport with plasma current. Our findings offer critical insights into the competing mechanisms that determine the density profile and present a valuable validation test for first-principles-based turbulent transport models TGLF in their prediction of particle fluxes. Understanding these dynamics is a vital step towards developing integrated scenarios for future reactors where precise control of the density profile is mandatory for achieving stable, high-performance plasma.

2. OHMIC DISCHARGES WITH DIFFERENT PLASMA CURRENT

The experiments were conducted on the EAST tokamak. To isolate the effect of plasma current (I_p) on particle transport, a series of dedicated Ohmic discharges were performed where I_p was systematically varied while rigorously keeping other key global parameters constant. The line-averaged density was feedback-controlled to a fixed value of 2.0×10^{19} m^{-3}. The toroidal magnetic field (B_t) was held constant at 2.3 T, and the plasma configuration (Lower Single Null) and elongation were maintained identical across all shots to ensure the same magnetic geometry. This experimental design ensures that any observed changes in plasma behavior can be unequivocally attributed to the variation in I_p.

Figure 1 illustrates the time evolution of key parameters for three representative discharges with I_p = 300, 400, and 500 kA. The plasma current and density were successfully maintained at their target values during the flat-top phase, which provided a stable window for detailed analysis. The most striking global observation is the clear enhancement of plasma performance with increasing current. The total plasma energy content, calculated from diamagnetic measurements, increased significantly with I_p, as shown in figure 1c. This indicates a substantial improvement in overall energy confinement time (τ_E), consistent with the well-established scaling laws for Ohmic plasmas, where τ_E typically scales positively with I_p.

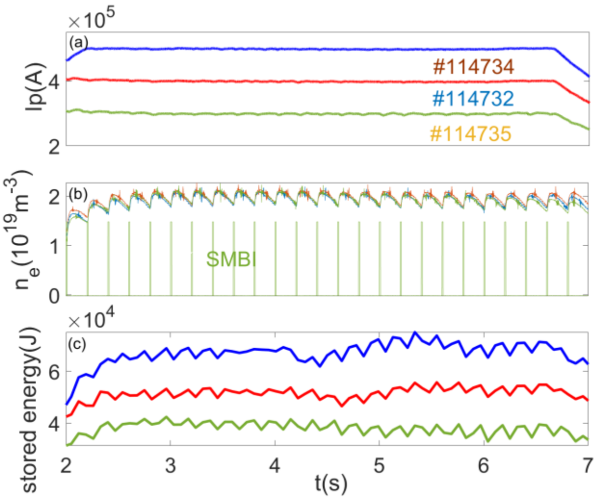

FIG. 1. Time evolution of (a) plasma current, (b) line-averaged density and SMBI to perturb the density, (c) plasma stored energy in three Ohmic discharges.

The profiles of electron density and temperature, measured by a combination of Interferometer, Reflectometer, and Electron Cyclotron Emission (ECE), reveal more nuanced information.As expected, the higher Ohmic heating power ($P_\Omega \propto I_p^2$) at elevated current led to a significant increase in electron temperature across the entire plasma radius. The 500 kA discharge exhibited the highest core T_e value (see figure 2a). In contrast, the density profiles, while having the same line-averaged value, displayed a notable change in shape. The core density peaking factor was found to decrease with increasing plasma current (Fig. 2b). The 500 kA discharge featured the flattest density profile among the three cases, despite having the best energy confinement. A key finding from the analysis of the normalized temperature gradient is that the core R/L_T was significantly larger in the low-current (300 kA) case (See figure 2d). This indicates that the core temperature gradient was steeper at lower current. The higher heating power at 500 kA, while producing a hotter plasma, resulted in a broader, flatter temperature profile with a reduced core gradient. This suggests that the improved confinement at high current allows the heat to be distributed more efficiently, preventing the formation of an extremely peaked core gradient.

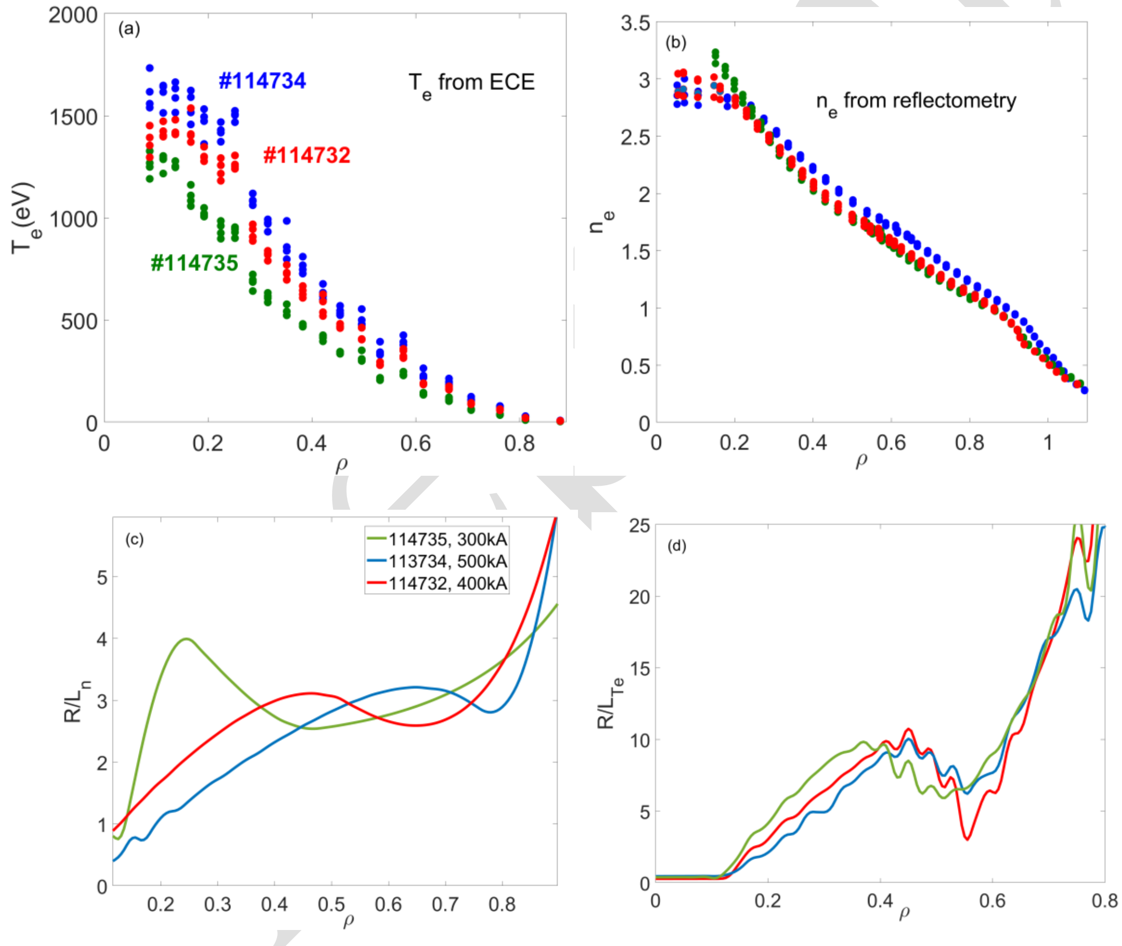

FIG. 2. (a) plasma electron temperature from ECE diagnostic, (b) electron density profile from reflectometry, (c) density gradient length, and (d) electron temperature gradient length. Four time slices from equilibrium state were chosen for each discharge.

The safety factor (q) profiles were reconstructed from equilibrium code calculations combined with muti-channel polarimeter on EAST tokamak [5]. As shown in figure 3, the core q-value decreased with increasing I_p, with the 500 kA discharge having the lowest minimum q. More importantly, the magnetic shear ($s = (r/q)(dq/dr)$), a key parameter for turbulence suppression, was strongly enhanced in the plasma core at higher currents. The 500 kA case displayed the most negative and strongly sheared magnetic configuration in the region from mid-radius to the core. This provides a clear rationale for the observed improvement in energy confinement, as strong shear is known to stabilize microturbulence. The fact that steeper pressure gradients (from R/L_n and R/L_T) are found at lower current, where shear is weaker, is consistent with the theory that reduced shear allows gradients to grow until they saturate at a higher level due to enhanced turbulence.

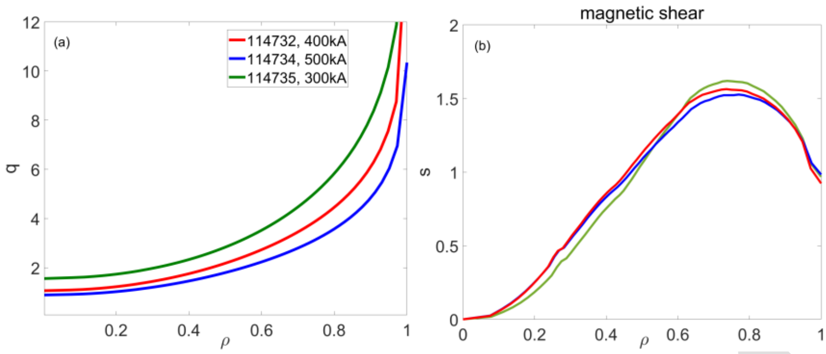

FIG. 3. Profiles of (a) safety factor calculated by EFIT combined with multi-channel polarimtry and (b) magnetic shear in Ohmic discharges with different plasma current.

3. ANALYSIS OF DENSITY MODULATION WITH SUPERSONIC MOLECULE BEAM INECTION

Figure 1b shows the density modulation wave using Supersonic Molecule Beam Injection (SMBI) [6]. The modulation frequency is about 5Hz, and the duty ratio is about 5%. We can get the particle diffusion coefficient and convective velocity through this method.

3.1. Particle source estimation

A principal challenge in quantitatively analyzing active particle transport experiments is the precise determination of the source function, *S(r, t)*, which represents the rate at which particles are introduced into the plasma per unit volume. An inaccurate source assumption can lead to significant errors in the inferred transport coefficients. In this study, we employed a sophisticated multi-method approach to accurately constrain the location and structure of the particle source generated by the supersonic molecular beam injection (SMBI).

First, the electron density response to a single SMBI puff was measured with high spatial and temporal resolution using a microwave reflectometer. The temporal derivative of the density response, $\partial n_e/\partial t$, immediately following the injection was calculated. The radial profile of the maximum value of $|\partial n_e/\partial t|$ was found to peak sharply at a normalized radial coordinate of $\rho\sim0.9$, as shown in figure 4a and 4b. This peak identifies the region of most rapid density build-up and is a strong indicator of the primary ionization source location. To provide independent theoretical validation, the source deposition was modeled using the BOUT++ framework [7]. The simulation, which includes neutral gas transport and ionization physics, predicted that the majority of the injected particles are ionized within a narrow region centered at $\rho\sim0.9$, shown in figure 4c. This result showed excellent agreement with the experimental measurement from the reflectometer.

Finally, the phase analysis of the density perturbations in the frequency domain during the continuous modulation provided a third, consistent confirmation. The phase of the density modulation, $\varphi(\rho)$, relative to the SMBI valve trigger signal, exhibits a characteristic minimum at the radial position where the source is dominant. This phase minimum corresponds to the point of direct forcing by the external source. Our analysis revealed this phase minimum to be located at $\rho\sim0.9$ for all investigated plasma current regimes, shown in figure 4d.

The consistent triangulation of the source location to $\rho\sim0.9$ using three independent methods—experimental measurement (reflectometer), numerical simulation (BOUT++), and spectral analysis (phase minimum)—provides a high degree of confidence in our source assignment. This rigorously constrained source function is subsequently used as a critical input for the perturbative transport analysis, ensuring the accuracy and reliability of the derived diffusion (D_{mod}) and convection (V_{mod}) coefficients.

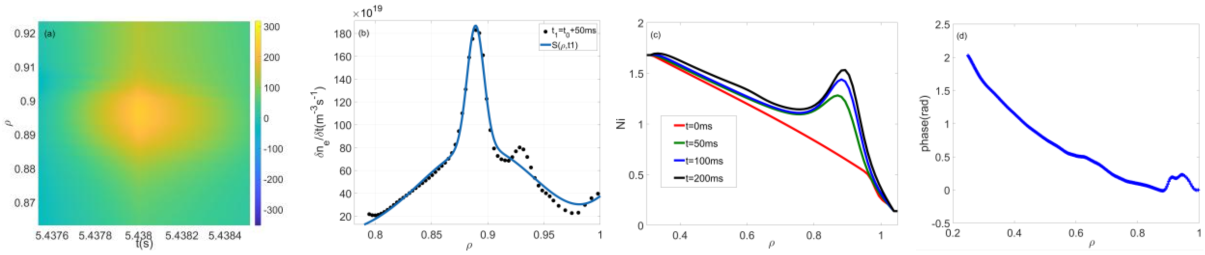

FIG. 4. (a) Density change by reflectometry, (b) shape of particle deposition, (c)ionized rate simulated by BOUT++, and (d)density modulation phase from FFT.

3.2. Particle transport coefficients from density modulation experiments

Based on the hybrid Genetic Algorithm and Quasi-Newton (GA/QN) optimization method developed by Ohtani et al. [9], the particle diffusion coefficient and convection velocity were successfully derived from density modulation experiments. This approach effectively reconstructs the radial profiles of density modulation amplitude and phase by combining global searching capability of GA and local refinement of Quasi-Newton (QN) method, preventing unphysical solutions and ensuring convergence to a realistic result.

As shown in figure 5a and 5b, excellent agreement is achieved between the experimentally measured amplitude and phase profiles (green lines) and the fitted results (red lines) using the GA/QN method, demonstrating the reliability of this analysis technique.

The derived transport coefficients are presented in figure 5c and 5d. The particle diffusion coefficient exhibits a gradual increase in the core region, followed by a significant rise beyond $\rho\sim0.7$. Similarly, the convection velocity remains relatively small in the core region but increases substantially from $\rho\sim0.7$ outward. This correlated increase in both in the peripheral region ($\rho > 0.7$) suggests enhanced anomalous transport mechanisms in the plasma edge, possibly related to increased turbulence activity or different instability regimes in this region.

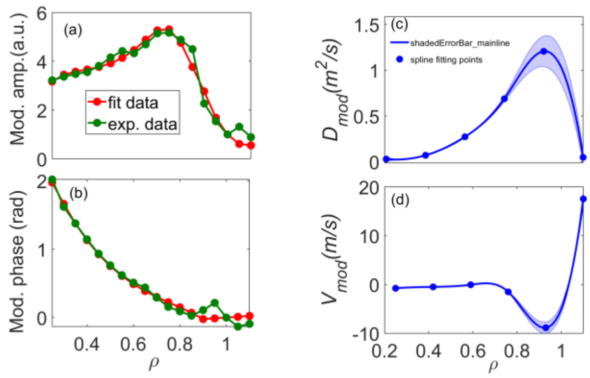

FIG. 5. (a) density modulation amplitude and (b) phase from reflectometer data by FFT analysis, and profiles of (c) particle diffusion coefficient, (d) convective velocity from density modulation experiment of Ohmic discharge with 500kA.

Based on the GA/QN optimization method developed by Kenji Tanaka et al. [8,9], the particle diffusion coefficient (D_{mod}) and convection velocity (V_{mod}) were derived from density modulation experiments under different Ohmic discharge currents. The modulation amplitude and phase profiles were first obtained through FFT analysis of three discharges, as shown in figure 6a and 6b.

The results reveal that the 300 kA discharge exhibits the smallest modulation amplitude and the flattest phase profile among the three cases. The reduced phase gradient is directly linked to the particle diffusion process, indicating enhanced transport. The derived transport coefficients confirm this observation: the 300 kA case shows the largest diffusion coefficient. To maintain a density gradient comparable to the other discharges, this case also exhibits the strongest inward convection. In contrast, the 500 kA discharge shows the smallest values of both diffusion and convection, suggesting suppressed turbulence levels at higher currents.

Notably, as shown in figure 6c and 6d, both D_{mod} and V_{mod} obtained from the modulation experiments exceed the neoclassical predictions by one to two orders of magnitude across all current levels. This significant enhancement demonstrates the dominant role of anomalous transport mechanisms over neoclassical processes in these Ohmic discharges. The disparity is particularly pronounced in the 300 kA case, where the turbulent transport is most enhanced.

These findings demonstrate a clear dependence of particle transport on plasma current in Ohmic discharges. The increased diffusion and required inward pinch at 300 kA indicate enhanced turbulent transport, while the reduced transport coefficients at 500 kA reflect improved confinement associated with higher current operations. The consistent discrepancy between experimental and neoclassical values underscores the prevalence of turbulence-driven anomalous transport in all investigated regimes.

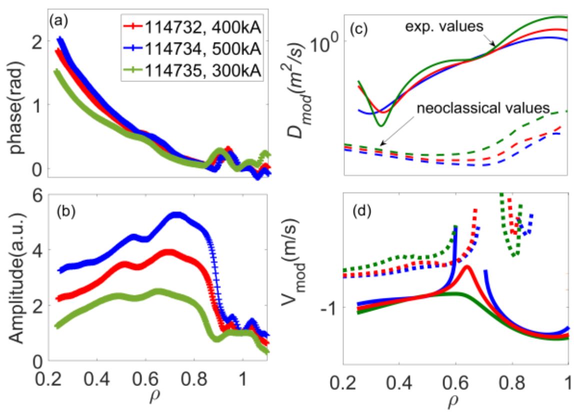

FIG. 6. Comparison of modulation characteristics and transport coefficients for three different Ohmic discharge currents (300 kA, 400 kA, and 500 kA). (a) Radial profiles of density modulation amplitude. (b) Radial profiles of density modulation phase. (c) Comparison of particle diffusion coefficients obtained from density modulation experiments (solid lines) and neoclassical predictions (dashed lines). (d) Comparison of convection velocities obtained from density modulation experiments (solid lines) and neoclassical predictions (dashed lines).

4. TUBULENCE ANALYSIS

The previous analysis of particle transport coefficients revealed a strong dependence on plasma current, with significantly enhanced diffusion and convection observed at lower currents (300 kA) compared to higher current operations (500 kA). While the modulation experiments clearly demonstrated the anomalous nature of this transport, exceeding neoclassical predictions by 1-2 orders of magnitude, the underlying physical mechanisms driving these current-dependent variations require further investigation. Particularly, the question remains why reduced current operation leads to enhanced turbulent transport and consequently necessitates stronger inward convection to maintain similar density gradients.

To address this fundamental question, we now turn to gyrokinetic analysis using the TGLF model [9] to examine the characteristics of microturbulence under different current conditions. The variation in plasma current affects multiple parameters simultaneously: higher currents typically produce stronger shearing rates, modify the safety factor profile, and alter both temperature and density gradients. These parameters collectively influence the stability boundaries and growth rates of various microinstabilities that drive turbulent transport. In this section, we employ TGLF simulations to analyse the spectral characteristics of turbulent modes—particularly their frequencies and growth rates—across different current regimes. By comparing these results with the experimentally observed density profiles and their gradients, we aim to identify whether specific instability types (such as ITG, TEM, or ETG modes) become dominant at certain currents and how their characteristics correlate with the measured transport levels. This analysis seeks to provide a physical explanation for the observed current dependence of particle transport and the resulting density profile formation.

The simulations confirm that the plasma core (ρ ~ 0.38) is dominated by Ion Temperature Gradient (ITG) turbulence across all investigated current levels, as shown in figure 7. A key finding is that while the ITG growth rate is higher at lower currents (300 kA), the core density profile is more peaked. Conversely, at higher currents

(500 kA) where the ITG mode is more stable (lower growth rate), the density profile is flatter. The decrease of growth rate in higher plasma current can be attributed to the higher magnetic shear in figure 3.

This seemingly counterintuitive result can be explained by the change in the characteristic real frequency of the ITG turbulence. Our analysis shows that as the plasma current decreases, the real frequency of the ITG mode also decreases, shifting toward the electron diamagnetic direction. This finding is pivotal and aligns with the theoretical framework established by Fable et al. [11], which identifies the normalized average mode frequency as a unifying parameter for turbulent particle pinch. According to this framework, the stationary density gradient is not solely determined by the turbulence intensity (growth rate) but is maximized when the turbulence is in a transitional state between pure ITG and pure TEM regimes. Although our simulations remain in the ITG dominated regime, the decrease in current moves the system closer to this optimal transitional state.

In the edge (ρ ~ 0.8), the simulations indicate that Trapped Electron Mode (TEM) turbulence is dominant. A key observation is that despite stronger magnetic shear at lower current (300 kA), which typically has a stabilizing effect, the growth rates remain high. Conversely, the growth rate is lower at high current (500 kA). This suggests that a different, collisionality-driven instability is likely competing with or replacing the standard TEM, which needs further investigation. But higher particle transport coefficients need higher turbulence level, and this is consistent with the D_{mod} and V_{mod} from the density modulation experiments.

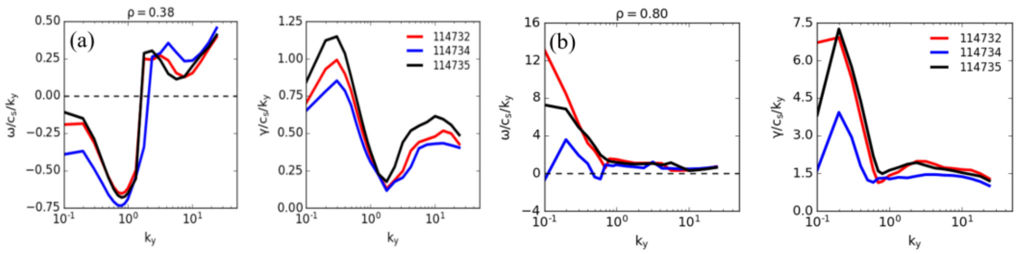

FIG. 7. Linear stability analysis from TGLF simulations for the three Ohmic discharges at (a) ρ ~ 0.38 (core region) and (b) ρ ~ 0.8 (edge region). The growth rate and real frequency are shown as functions of the binormal wavenumber.

5. SUMMARY

This study systematically investigates the dependence of particle transport on plasma current in Ohmic discharges on the EAST tokamak. Through carefully controlled experiments with fixed line-averaged density and magnetic configuration, three plasma current levels (300 kA, 400 kA, and 500 kA) were compared. Results show that higher plasma currents lead to improved energy confinement and elevated electron temperatures, yet surprisingly result in flatter core density profiles despite reduced turbulent transport.
Density modulation experiments were conducted to get the transport coefficients. The particle source from supersonic molecular beam injection (SMBI) was localized at ρ~0.9 using reflectometry, simulation, and phase analysis. Genetic Algorithm-based transport analysis revealed that both diffusion coefficient and inward convection velocity decrease significantly with increasing plasma current, exceeding neoclassical predictions by 1–2 orders of magnitude, confirming turbulence-dominated transport.
TGLF simulations identified Trapped Electron Modes (TEM) as the primary turbulence driver in the edge region, with growth rates inversely correlated with plasma current. The suppression of TEM instability at higher currents provides a unified explanation for the observed reduction in transport coefficients and improved confinement. These findings offer critical insights into current-dependent particle transport mechanisms and provide valuable validation for turbulent transport models in future reactor-scale plasmas.

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