MFP-39 AAPPS-DPP2018

2nd Asia-Pacific Conference on Plasma Physics, 12-17,11.2018, Kanazawa, Japan

Nonlinear gyrokinetic analysis of linear Ohmic confinement to saturated Ohmic confinement transition

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The transition of energy confinement time τ_E from the linear Ohmic confinement (LOC) regime to saturated Ohmic confinement (SOC) regime in Ohmic plasmas is a long-lived conundrum in tokamak fusion plasmas. It is found in early experiments in the Alcator C tokamak [1] that the energy confinement time τ_E is linearly proportional to the line-averaged electron density $\bar{n}_e$, which is referred as the LOC regime. The confinement time saturates in the SOC regime as the density increases, showing weak dependency on the density.

Though LOC-SOC transition is studied widely in experiments and many devices, it remains as a mystery and the understanding of the underlying physics is still poor. Interpretation of early Ohmic plasmas is on the basis of a theoretical consideration [2] that trapped electron modes at low density and ITG modes at high density, presumably assuming TEM is stabilized by collision and ITG becomes dominant. Experiments in ASDEX Upgrade obtained a consistent result [3] and a transition from TEM to ITG was observed as collisionality increases [4]. The study of Alcator C-Mod tokamak Ohmic plasmas and comparisons with local gyrokinetic simulations address the importance of collision in stabilizing TEM by scattering trapped particles with justifications in a linear limit [5]. As far as we know, a robust and concrete theoretical understanding of the mechanism governing the LOC regime and the transition to SOC is still lacking.

Here we present the first investigation of LOC-SOC transition with the first principle nonlinear global gyrokinetic simulations using gKPSP [6-8]. In this study, by varying a single parameter plasma density n, the confinement time estimated by $\tau \propto 1/\chi_{eff}$ shows a transition from a linearly increasing regime to a saturation regime as the plasma density increases, as shown in Fig. 1b. The effective transport diffusivity is defined as $\chi_{eff} \equiv \frac{n_e\chi_e\nabla T_e + n_i\chi_i\nabla T_i}{n_e\nabla T_e + n_i\nabla T_i}$, where $n_{e(i)}, T_{e(i)}$ and $\chi_{e(i)}$ are density, temperature and heat diffusivity for electron (e) and ion (i), as presented in Fig. 1a. The above nonlinear result follows the trend from the mixing length quasilinear estimation for the heat transport plotted in Fig. 1c. In the figure, the inverse of the mixing length estimated heat transport $1/\chi_{MLE}$ is plotted. A transition of trapped electron dominant heat transport from TEM to ion dominant heat transport from ITG is observed when the LOC to SOC transition occurs. In Fig. 1c, the black-white color shows qualitatively the strength of dominant modes transits from TEM to ITG as density increases. It is also observed that the particle flux changes gradually from outward to inward as the mode transits from TEM to ITG, as one can figure it out in Fig. 1a. The underlying physical effects in this LOC to SOC transition can be understood by analyzing the phase space dynamics. This study is dedicated to demonstrating a theoretical basis for the understanding of the LOC-SOC transition physics, focusing on the density induced collisional effects. Possible physics relating to experiments will also be discussed.

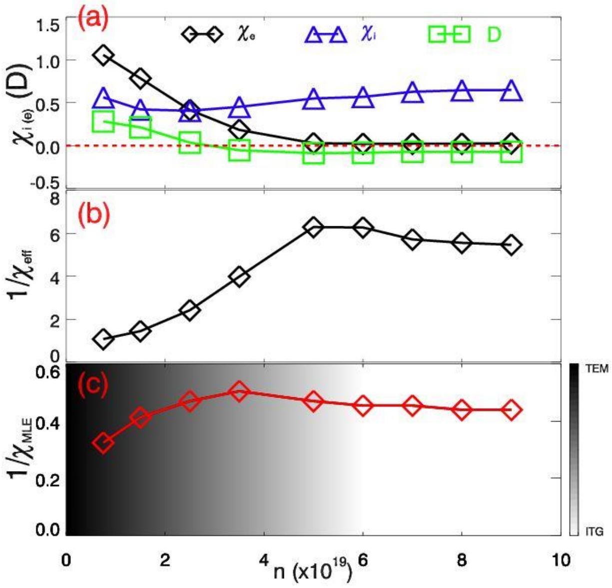

Figure 1. (a) ion (χ_i, blue line), electron (χ_e, black line) heat diffusivities and particle flux diffusivity (D, green line), normalized to gyro-Bohm diffusivity $\chi_{GB} \equiv \rho_i^2 V_{Ti}/a$; (b) the inverse of the effective heat diffusivity ($1/\chi_{eff}$); (c) the inverse of the mixing length estimated heat transport ($1/\chi_{MLE}$) as a function of density (n).

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