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Full-f gyrokinetic simulations of LOC-SOC transition

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Ohmic L-mode experiments on the Tore Supra typically show linear and saturated ohmic confinement (LOC-SOC) transition [1]. The LOC phase is characterized by low density, high Z_{eff} due to carbon impurity, linear increase of the energy confinement time τ_E with electron density, and turbulent spectra with quasi-coherent modes [2]. On the other hand, the SOC phase is characterized by high density, low Z_{eff}, saturation of τ_E, and broad turbulent spectra. During the transition, intrinsic rotation profiles change in the co-current direction [3], which is in the opposite direction from other devices [4] and is a unique feature of the Tore Supra. To understand these complicated transport properties of particle, impurity, momentum, and energy is one of critical issues in fusion science. So far, this issue was addressed based on local δf gyrokinetic models, and transition of the dominant micro-instability from trapped electron modes (TEMs) to ion temperature gradient driven (ITG) modes was reported [5]. This transition occurs due to changes in collisional TEM stabilization and ITG stabilization due to dilution of bulk ions, which are characterized by the electron collisionality ν_e^* and Z_{eff}, respectively. In Ref.[5], the coherent and broad turbulent spectra was reproduced via a synthetic diagnostic of turbulent spectra, while only energy transport was discussed. In this work, we address also particle, impurity, and momentum transport channels via long time numerical experiments using a global full-f gyrokinetic code GT5D [6].

In this work, we analyze Tore Supra ohmic discharge 48102 [3], in which the toroidal field is B=3.7T (q_{95}~4), the major radius is R=2.43m, the minor radius is a=0.7m, the normalized machine size is a/ρ_i~500, and the joule heating is estimated as P_j~600kW. We focus on two time slices in the LOC phase (t~3.1s, n_e~2.4×10^{19}m^{-3}, Z_{eff}~3.1, ν_e^*~0.04) and the SOC phase (t~6.1s, n_e~3.7×10^{19}m^{-3}, Z_{eff}~1.3, ν_e^*~0.3). In order to reduce the computational cost, the plasma size a/ρ_i is reduced by a half, and the heating power is also scaled as a half, which corresponds to a Bohm scaling setting. Based on the profiles of joule heating and radiation loss, heat source and sink are imposed on axisymmetric components. Here, the edge density, rotation, and temperature profiles are fixed to experimental ones on average by the Krook type sink operator. The initial density and temperature profiles are given by the experiment, while the initial rotation profile is chosen as rigid rotation with the edge rotation velocity, which is in the counter-current direction due to the toroidal ripple and is almost unchanged between the LOC and SOC phases. We compute real mass kinetic electrons, deuterium, and carbon using (N_R,N_φ,N_Z, $N_{v\|}$,N_μ)=(240,48,240,96,20)~10^{10} grids in a 1/6 wedge torus up to ~15 msec, which require ~50M node-hours per shot on Fugaku.

Linear eigenmode spectra show transition from TEM in the LOC phase to ITG in the SOC phase, as shown in the local analyses at r/a~0.37 in Ref.[5]. However, global eigenmode structures of TEM and ITG are peaked in the edge regions, which have steep density and temperature gradients, and turbulent fluctuations propagate from edge to core via avalanches. TEM has larger saturation amplitudes of density fluctuations than ITG, which is consistent with density fluctuation measurements in Ref.[1]. The ratio of τ_E between the two time slices is close to the experiment. In the LOC phase, particle fluxes of deuterium and carbon are much larger than electron transport and neoclassical transport, where exhaust of carbon and pinch of deuterium occur due to strong turbulent ion mixing. Intrinsic rotation develops in the counter-current direction with respect to the edge rotation. Energy transport is dominated by electrons, while deuterium and carbon make non-negligible contributions. On the other hand, in the SOC phase, the ambipolar condition is satisfied between electron and deuterium, and particle transport is small. Intrinsic rotation is still in the counter-current direction, but is changed in the co-current direction from the LOC phase. Energy transport is dominated by deuterium in the ITG turbulence. These features are qualitatively consistent with the experiment [3][5].

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