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Simulation study of particle transport by weakly coherent mode in the Alcator C-Mod tokamak

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I-mode, featuring a temperature pedestal but without a density pedestal, has been explored on many tokamaks.[1] It is typically accessed with the ion $\mathbf{B}\times\nabla B$ drift away from the active X-point. Contrary to its H-mode-like energy confinement, I-mode exhibits L-mode-like particle confinement,[2] which avoids the impurity accumulation. Due to the lack of density pedestal, the pressure gradient and bootstrap current in the I-mode pedestal are smaller than those in the ELMy H-mode pedestal. This makes I-mode naturally stable to the edge-localized modes (ELMs).[3] Combining both the advantages of L- and H-modes, I-mode is a promising high-performance operation regime for reactor-scale tokamak devices.

The transition from L-mode to I-mode is accompanied by the changes in edge density, temperature, and magnetic field fluctuations. The mid-frequency fluctuations are strongly suppressed, which was observed experimentally to correlate well with the reduction in the effective thermal diffusivity in the pedestal region.[4] Meanwhile, a high-frequency weakly coherent mode (WCM) appears and its amplitude was found to correlate positively to the particle flux across the last closed flux surface (LCFS),[3] suggesting that the WCM is responsible for maintaining high particle and impurity transport in the I-mode pedestal. Up to now, there is still no consensus on the fundamental mechanism behind the WCM and the comparison of its produced transport in simulations with the experimental results is not so satisfactory.

We conduct a simulation study of the physical mechanisms behind the WCM and its produced particle transport in the I-mode edge plasmas by using the BOUT++ code.[5] The WCM is identified in our simulations by its poloidal and radial distributions as well as its frequency and wavenumber spectra. Its produced radial particle flux is calculated and compared with the experimental value. The good agreement indicates that the WCM is an important particle transport channel in the I-mode pedestal. It is found that the WCM can transport particles across the strong outer shear layer of the E_r well established in the formation of I-mode, based on which a possible explanation is provided why I-mode does not feature a density pedestal. The key point lies in the change of the cross-phase between the electric potential and density fluctuations induced by the $\mathbf{E}\times\mathbf{B}$ Doppler shift. In the strong shear layer, although the electric potential fluctuation is significantly suppressed, the cross-phase is close to $\pi/2$, resulting in a strong drive of the density fluctuation and particle transport. To identify the physical nature of the WCM, the linear dispersion relation equation is derived in the slab geometry. We find a drift Alfvén wave (DAW) instability driven by the electron density and temperature gradients. The growth rate and frequency of this DAW instability show similar dependence on the parallel resistivity and the parallel electron pressure gradient and thermal force terms in the parallel Ohm's law as the simulated linear instability under a typical toroidal mode number n for the WCM. Therefore, we argue that the DAW instability is possible the main component of the WCM.

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