Transport properties of trapped-electron-mode turbulence interacting with tearing modes in tokamak plasmas

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Summary: Turbulence transport behavior often intertwines with magnetic topology due to the formation of magnetic islands (MIs) in tokamak plasmas. This study investigates a novel transport property of trapped electron mode (TEM) turbulence interacting with dynamic MIs generated by MHD resistive tearing mode (RTM) in simulations using a compact Landau fluid model. Turbulent particle and heat fluxes display characteristics of oscillatory transport in a multi-scale TEM-RTM turbulence, where both TEM and RTM instabilities are moderate. Specifically, turbulent electron heat flux bursts periodically, synchronized with the magnetic reconnection and disconnection of the m/n=2/1 MIs, while turbulent ion transport alternates between inward heat flux (thermal pinch) and outward heat flux (thermal diffusion), even becoming completely inward with reduced oscillatory amplitude for more unstable RTMs. Here, m and n represent the poloidal and toroidal mode numbers, respectively. The underlying physical mechanisms are analyzed by examining the transport response to dynamic MIs. It is shown that the 2/1 mode is recurrently excited, accompanied by alternating magnetic reconnection (MIs growing) and disconnection (MIs shrinking), resulting in repeating cycles of n=1 RTM eigenmode states. Simultaneously, the 3/1 mode with MIs of a specific width plays a critical role in regulating these cycles through toroidal mode coupling with the adjacent 2/1 mode. These findings may offer new insights into understanding the oscillatory transport phenomena experimentally observed in tokamak plasmas with MI dynamics.

Background and motivation: Coexistence and interaction of multiple modes with different (even comparable) scales are common in magnetically confined plasmas due to abundant instabilities, particularly in fusion plasmas. On one hand, various macroscopic MHD instabilities, such as TMs, can nonlinearly interplay with microscopic drift wave turbulence, including the ion temperature gradient (ITG) mode and TEMs, thereby regulating turbulence transport. On the other hand, large-scale MIs may form through the so-called magnetic reconnection mechanism as TM instabilities evolve. Larger MIs can potentially alter the equilibrium magnetic topology of the tokamak, creating a radial magnetic field disturbance that enhances radial particle and heat transport. Consequently, TMs could significantly degrade the confinement performance of the device. Earlier studies on the nonlinear interaction between RTMs and ITG turbulence have been consistently conducted using fluid and/or gyro-Landau fluid models in slab geometry[1], providing preliminary insights into the multi-mode, multi-scale physics. Subsequently, static MIs have been embedded in drift wave turbulence in toroidal plasmas as an initial attempt to explore more realistic interactions[2], considering the complexity of the mode coupling problem involving nonlinear spectral and linear geometric coupling effects. However, it is noted that the assumption of static MIs inherently neglects their response to micro-turbulence and the impact of dynamic MIs on turbulence. Simulations incorporating naturally evolving MHD fluctuations and micro-turbulence are therefore necessary for further study.

It is noteworthy that the coexistence of MHD MIs and TEM turbulence, primarily driven by the trapped electron temperature gradient, has been experimentally observed[3]. Furthermore, electron transport responses to MI dynamics have been analyzed based on experimentally diagnosed electron temperature fluctuations in tokamak plasmas. An intermittent or oscillatory transport behavior has been described, wherein turbulence transport interacts with the magnetic topology associated with MI dynamics[4, 5]. While it is generally proposed that turbulence spreading into the MIs may dominate the transport response to MI dynamics, other mechanisms warrant much deeper investigation.

Simulation results and underlying mechanisms: Motivated by the concerns outlined above, this study simulates the nonlinear interaction between TEM turbulence and RTM fluctuations using a Landau fluid model combined with the Weiland model for the nonadiabatic trapped electron response in tokamak plasmas [6]. The simulation results reveal that turbulent particle and heat fluxes exhibit oscillatory transport behavior, as shown in Fig. 1. The turbulent electron heat flux periodically bursts, synchronizing with the magnetic reconnection and disconnection of the 2/1 MIs, while turbulent ion transport alternates between inward heat flux (thermal pinch) and outward heat flux (thermal diffusion). The period and amplitude of these bursts, as well as the integral transport, are influenced by the strength of both TEM and RTM instabilities, which are closely linked to parameters such as plasma beta, resistivity, and viscosity. For instance, the integral ion heat transport may become thermal pinch for strong RTM fluctuations with higher resistivities.

The underlying mechanisms are analyzed by examining the transport response to dynamic MIs, with an emphasis on the roles of toroidal mode coupling (TMC) in geometric space and nonlinear mode coupling (NMC) in Fourier-spectral space, particularly the inverse energy cascading. It is shown that the 2/1 mode is recurrently excited, accompanied by alternating magnetic reconnection (MI growth) and disconnection (MI shrinkage), resulting in repeating cycles of *n*=1 TM eigenmode states, as illustrated in Fig. 2. Simultaneously, the 3/1 mode with MIs of a specific width plays a critical role in regulating these cycles through TMC with the adjacent 2/1 mode.

Conclusion: The interaction between TEM turbulence and RTM fluctuation with MI dynamics could result in oscillatory turbulence transport behavior. These findings may provide new insights into understanding the oscillatory transport phenomena experimentally observed in tokamak plasmas with MI dynamics.

References

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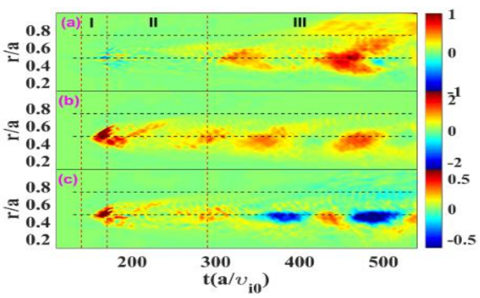

Fig.1 Spatio-temporal evolution of the turbulent particle flux, Γ_{ne}, (a), and the electron (b) and ion (c) heat fluxes, $Q_{i,e}$, in TEM-RTM turbulence with MIs dynamics.

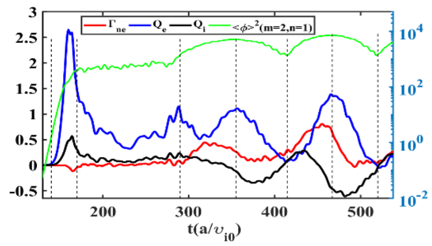

Fig.2 Temporal evolution of the radially-averaged fluxes Γ_{ne} and $Q_{i,e}$ in the 2/1 MIs region. For comparison, the temporal evolution of the potential energies of both 2/1 and 1/3 modes is plotted using the second vertical axis for reference.