Multi-scale interaction in turbulence and MHD system in magnetized plasmas

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In fusion plasmas, various fluctuations with different time and spatial scales from micro-scale turbulence associated with electron and ion motion to macro-scale MHD mode. Such fluctuations lead to macro-scale secondary fluctuations and zonal flows, and influence on plasma stability and transport. In this report, spatio-temporal structure of zonal flow and associated intermittent transport dynamics, the effects of interaction between micro-scale turbulent fluctuations, and also those between turbulence and MHD mode on transport and MHD phenomena will be discussed based on theory and simulation. As a result, a robust oscillatory zonal flow with finite frequency in mixed MHD and ITG turbulence is created due to the multi-scale interaction so that the ion heat transport is not efficiently suppressed. This implies probable degeneration of the favorable role of ITG zonal flows by MHD fluctuations.

1. Introduction

The physics of multi-scale turbulence in magnetic fusion plasmas has been attracted much attention recently [1-3]. Different scale fluctuations, such as the macro-scale MHD such as tearing modes and the ion-scale typically like ion temperature gradient (ITG) fluctuation, may interplay each other directly or indirectly through a zonal flow, which has been widely recognized as a stationary coherent structure in magnetic confinement plasmas. The zonal flows can efficiently regulate the turbulent fluctuation and suppress the turbulent transport. The spatio-temporal nature of the zonal flows is important in plasma transport. In a toroidal plasma such as tokamak, the zonal flow is geometrically coupled with a geodesic acoustic mode (GAM) so that it behaves oscillatory. This oscillating property reduces its favorable suppression role in transport [4]. On the other hand, it is expected to properly utilize large-scale MHD fluctuation to control turbulent transport while it may cause a plasma disruption. Meanwhile, the zonal flow, likely excited by MHD fluctuations, may hopefully play an essential role in the formation of transport barrier. Here we perform a multi-scale turbulence simulation to investigate these issues. We focus on the zonal flow dynamics, especially its spatio-temporal characteristics in different scale turbulent fluctuation and ion transport.

2. Multi-scale Gyrofluid simulation

Aiming to understand underlying physics of multi-scale nonlinear interaction, a 5-field gyrofluid model in slab geometry is employed to perform the multi-scale MHD and ITG turbulence simulation [4]. The equilibrium magnetic flux is assumed as

\[ \psi_0(x) = \psi_0 \cosh^2(x/L_x), \]

with \( L_x \) being the characteristic length. The corresponding magnetic field \( B_z(x) \) around the surface \( x=0 \) is similar to that in the slab model of tokamak plasma. Under this equilibrium, both the resistive kink-tearing modes (RKTM) and the ITG fluctuations can coexist through adjusting the ITG parameter \( \eta_i \) and the resistivity \( \eta_i \), which govern the ITG and MHD instabilities, respectively. Fig.1 clearly shows that as the resistivity increases, the RKTM becomes more unstable while the ITG instability is almost not influenced. On the other hand, the ion temperature gradient does not affect the MHD stability.

![Fig.1 Linear growth rate of both RKTM and ITG modes for different resistivity \( \eta \) and ion temperature gradient \( \eta_i \).](image-url)

Guided by the linear stability analysis in this simplified multi-scale model, we mainly perform nonlinear simulations with relatively more unstable RKTM or ITG instability to understand the mutual influence on each other. In the case with larger growth rate of ITG mode than the RKTM, the growth of MHD fluctuation is accelerated by the linearly growing ITG mode through the nonlinear coupling. The MHD fluctuation contributes to saturate the ITG modes. On the other hand, when the growth rate of MHD mode is larger than the ITG, ITG mode is saturated first at low level by the MHD fluctuation, then, it is also accelerated by the MHD through nonlinear mode coupling. It is observed that a robust zonal flow is generated near the
singular layer of RKTM even if the ITG mode is stable as shown by Fig.2 and Fig.3. It is examined that the radial gradients of Reynolds and Maxwell stresses are changed from an oscillating nature in time in pure RKTM into an exponential growth due to nonadiabatic electron response and/or ion diamagnetic drift effect in multi-scale fluctuations. The zonal flow is mainly driven by the magnetic fluctuation as well as the fluctuating current. However, it seems not to be able to efficiently stabilize the turbulence and suppress ion transport, even if the ITG instability is strong. Although the simulation here is performed in a slab, this result implies that the MHD fluctuation may degenerate the favorable suppression role of ITG zonal flows in ion transport in week and/or negative shear tokamak plasmas, especially in the region near the minimum $q$, where the internal transport barrier is expected.

![Figure 2](image1.png)

**Fig.2** Time evolution of potential energy for different components. Inset shows the ZF structure. $\eta = 5 \times 10^{-4}$, $\eta = 1.25$.

![Figure 3](image2.png)

**Fig.3** The zonal flow structure before the turbulence saturation in the simulation of Fig.2.

**3. Zonal flow with finite frequency:**

To explore the physical mechanism of the zonal flow effect on ion transport in multi-scale MHD and ITG turbulence, we analyze the time-dependent wavelet energy spectra during the zonal flow evolution and the temporal Fourier spectra in the quasi-steady state of the turbulence. It is found that the zonal flow in multi-scale turbulence behaves oscillatory in time after the turbulence saturation. The zonal flows develop to have a finite real frequency in the quasi-steady due to the nonlinear interaction between macro-scale MHD and micro-scale ITG fluctuations, as shown in Fig.3. The frequency is measured numerically at around $(0.1 \sim 0.2)\omega_c$. Fig.5 shows that ion heat transport is not suppressed by this oscillatory flow. This new characteristics is similar to the GAM dynamics in a toroidal plasma, but it is caused by the multi-scale nonlinear interaction. A modeling analysis about the generation of finite frequency zonal flows due to the multi-scale fluctuation interaction is under the development.

![Figure 4](image3.png)

**Fig.4** The frequency spectra if zonal flows in quasi-steady states in two simulations with different ion temperature gradient.

![Figure 5](image4.png)

**Fig.5** The comparison of ion heat transport in the cases with and without zonal flows.

**References**