§7. Excitation of MHD Mode due to Multi-scale Interaction in a Quasi-steady Equilibrium Formed by a Balance between Micro-turbulence and Zonal Flow

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This is the first numerical simulation demonstrating that a macro-magnetohydrodynamic (macro-MHD) mode is excited as a result of multi-scale interaction in a quasi-steady equilibrium formed by a balance between micro-turbulence and zonal flow based on a reduced two-fluid model. This simulation of a macro-MHD mode, a double tearing mode, is accomplished in a reversed shear equilibrium that includes zonal flow and turbulence due to kinetic ballooning modes.

Macro-MHD activities substantially degrade magnetic confinement of toroidal plasmas by producing global fluctuations, and the evolution of these activities is observed in experiments. Such macro-MHD instabilities have been analyzed by nonlinear MHD simulations starting from linear instability growth under a static equilibrium. However, observations in the experiment apparently include micro-turbulence and zonal flow, and the macro-MHD can nonlinearly originate from turbulent fluctuations. In fact, MHD activities are observed before the disruption in reversed shear plasmas with a transport barrier related to zonal flows and micro-turbulence, and micro-turbulence is observed in Large Helical Device plasmas that usually exhibit MHD activities. In these experiments, the turbulence can affect macro-MHD in several ways through multi-scale interactions. In order to understand the growth of fluctuation observed in the experiments, we have to carry out nonlinear numerical simulation including not only the MHD instability but also the micro-turbulence and zonal flow created by the turbulence. Multi-scale interactions play key roles in understanding effects of micro-turbulence on macro-MHD mode. A typical multi-scale interaction in the magnetic confinement is the interaction between micro-turbulence and zonal flow. Effects of micro-turbulence on macro-MHD mode through nonlinear mode coupling are studied theoretically and numerically, and they are described by a negative eddy viscosity or by an anomalous resistivity. On the other hand, the zonal flow caused by the turbulence can also affect the macro-MHD instability through the shearing of its radial structure. These effects of turbulence on macro-MHD should be simultaneously taken into account in numerical simulations. Our goal is to understand the mechanism of macro-scale MHD instability in the reversed shear plasmas based on the analysis of multi-scale interactions among macro-scale MHD, micro-turbulence, and zonal flows.

We carry out three-dimensional numerical simulations of a reduced set of two-fluid equations that extends the standard reduced two-fluid equations, by including temperature gradient effects. We have found that the macro-MHD mode, double tearing mode, grows from the turbulent fluctuations in a quasi-steady equilibrium formed by a balance between the turbulence and zonal flow. Only after obtaining the quasi-equilibrium, which includes the micro-turbulence, zonal flow, and two resonant surfaces of q=2 are we able to obtain this simulation result of macro-MHD mode. The present multi-scale simulation is more realistically comparable to the experimental observation of growing macro-MHD activity than earlier MHD simulations starting from linear macro-instability growth in a static equilibrium. This is because plasmas in experiments inherently include turbulent fluctuations and zonal flows and they apparently affect the growth of macro-MHD mode through multi-scale interactions.

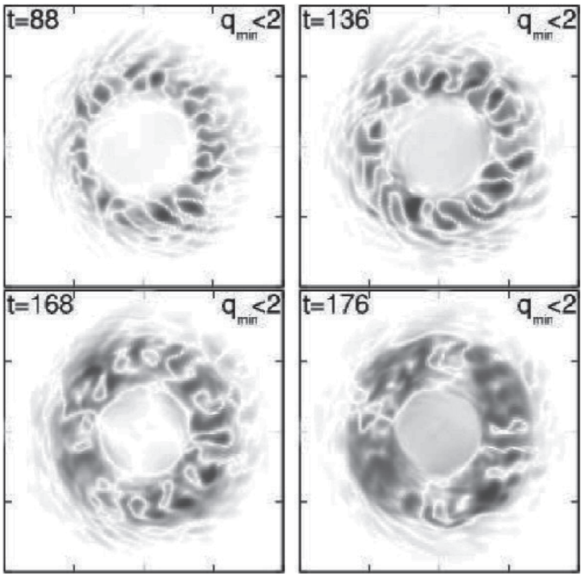

Fig.1. Time evolution of the electric potential on the same poloidal section. The first frame shows quasi-steady equilibrium. The macro-MHD appears at t=168.

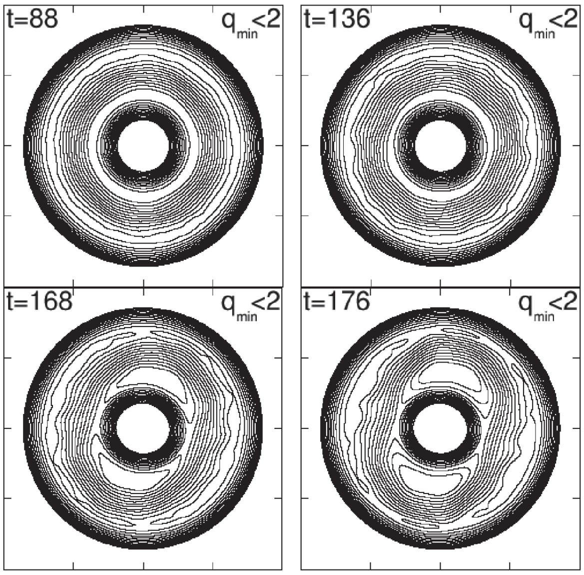

Fig.2. Time evolution of the equi-contour of helical flux of m/n=2 on the same poloidal section. The magnetic islands of macro-MHD appear appears at t=168.

Reference
1) A. Ishizawa and N. Nakajima, Phys. Plasmas **14**, 040702 (2007).