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Experimental Studies of Turbulence and Zonal Flow in a Laboratory Plasma

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The turbulence in magnetically confined plasma is an essential factor to determine the plasma transports and the resultant thermal structure of the plasma. Since a transport barrier (or H-mode) was discovered in 1982, it has been known that turbulence-driven transport can bifurcate to produce variety of plasma structures. One of the findings after the research over more than two decades is that the structure of electric field has an impact on turbulence and transport and induces a transition to a new thermal structure. In other words, shear structure of electric field can suppress the microscopic turbulence. It has been found that the linkage between macroscopic electric field (ExB flow) and microscopic turbulence can be a major mechanism to establish transport barriers.

On the other hand, recent researches in simulation and theory have revealed that the turbulence should generate a mesoscopic structure, termd zonal flows, through nonlinear wave-wave couplings, and that the interplay between turbulence and zonal flows should have a fundamental effect on the saturation level of turbulence and transport. The zonal flows have a symmetric structure of m-n=0 with a finite radial wave number, where m and n are the poloidal and toroidal mode numbers, respectively. The zonal flows do not contribute to any cross-field transport owing to its symmetric nature. Since the energy is approximately conserved between turbulence and zonal flows, their energy participation should determine the transport level. At present, the research on the plasma transport and structure is being developed toward a new paradigm based on the relationship between three major elements, turbulence, zonal flows, and macroscopic electric field

In the plasma experiments, to provide the evidence of 'the presence of the zonal flows' was a crucial issue to support the paradigm shift. In 2004, the presence of the zonal flows was experimentally proven in Compact Helical System (CHS). The experiment confirmed, using twin heavy ion beam probes, the presence of mesoscopic fluctuating structure characterized by a long-distance correlation (or symmetric nature) with a finite radial wave number. The diagnostics could reveal nonlinear or causal linkage between turbulence and zonal flows. The time-dependent analysis using a wavelet showed that the intermittent behavior of turbulence was related with the phase of zonal flows. In addition, the analysis clearly demonstrated that the macroscopic structure of electric field should affect the turbulence-driven transport.

In other laboratory plasmas, a number of observations and analyses have been performed on the causal relationship between turbulence and zonal flows. Many observations on the geodesic acoustic mode (GAM), an oscillatory branch of the zonal flows, have been accumulated from many toroidal machines. Advanced analyses have been applied on the accumulated data to extend the understanding the physics of zonal flows. For example, the bicoherence analysis is a powerful tool to extract a nonlinear process between turbulence and zonal flows. In JFT-2M, the bicoherence analysis succeeded to quantify the nonlinear interaction between the background turbulence and the GAM.

Finally, structure or phenomena related to turbulence is ubiquitous in nature. The examples include band-like structure in rotational planets such as Jupiter, jet stream, solar tacocline and so on. The laboratory experiments of magnetically confined plasma have been recently entered into the stage of clarifying the mechanisms of plasma structural formation through the observation on dynamics and structure of zonal flows and on its interaction with turbulence. Such experiments will contribute to understanding of various turbulence-related phenomena in the universe. The paper will present recent experimental results, in CHS, on the three elements (e.g., turbulence, zonal flows, macroscopic electric field), and their linkages.