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Geometry-induced zonal flow activation and turbulent transport reduction in magnetically confined plasmas

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Magnetically confined high-temperature plasma is regarded not only as the medium of fusion reactions, but also as an attractive nonequilibrium system that realizes an extreme spatial inhomogeneity/gradient embedded in external fields with the geometric flexibilities, where the magnitude of the temperature gradient often exceeds that in the stars like the sun. Then, one of the most prominent physical processes is spontaneous emergence of mesoscopic coherent structures, e.g., zonal flows, geodesic acoustic oscillations, and radially elongated streamers, which are nonlinearly excited in microscopic turbulence. An important finding, which has been discovered in earlier works, is the suppression of turbulent transport by zonal flows[e.g., Ref. 1]. The zonal-flow generation is now recognized as a key mechanism leading to improved plasma confinement, or to enhance more the inhomogeneity. The zonal-flow dynamics in general non-axisymmetric three-dimensional(3-D) magnetic fields is yet to be fully clarified, but the diversity of the magnetic geometries strongly motivates us to explore capabilities of enhancing the zonal-flow formation.

In this talk, we present the recent progress in theoretical and numerical studies on the magnetic-geometry-induced activation of the zonal flows. The high-dimensional extreme value problems are solved in this formalism. Since the zonal-flow-activated plasma is identified as the local/global optimum solution in the multi-dimensional Fourier space of the magnetic geometry, a joint approach of the turbulence physics, mathematics, and informatics is crucially important. So far, by extending a conventional simplified model[3], the ion temperature gradient(ITG) driven turbulent transport including the zonal-flow effects is modeled into a nonlinear function only with the geometric quantities, such as the magnetic field intensity, the normal and geodesic curvatures[4], where the geometric dependence of the zonal-flow damping is identified by means of gyrokinetic simulations with several non-axisymmetric magnetic configurations, as shown in Fig.1. Utilizing mathematical optimization techniques with the above extended model, numerical explorations of 3-D magnetic geometry are carried out. Here, a local gradient based optimization scheme is used. Nonlinear gyrokinetic ITG turbulence simulations for the obtained optimum magnetic configuration revealed the activation of zonal flows, as shown in Fig.2. The turbulent heat transport level is reduced by a factor of 0.6. Significant enhancement of the zonal-flow generation also leads to less stiffness, i.e., the slope of the turbulent transport level with respect to the ion temperature gradient is decrease in the optimized magnetic configuration found here.

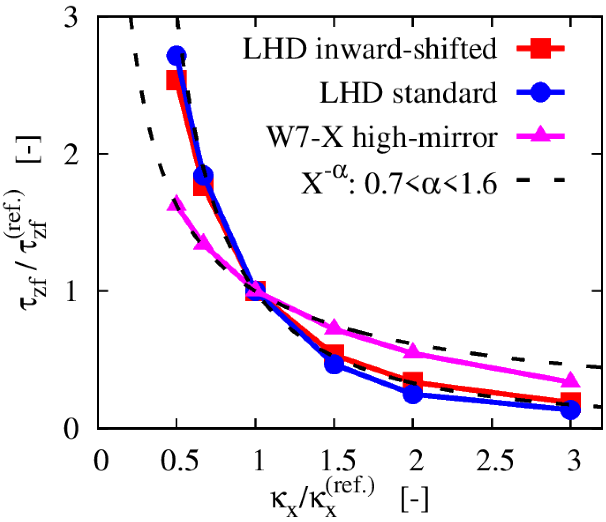

Figure 1: Geodesic curvature dependence of zonal flow decay time for several magnetic configurations.

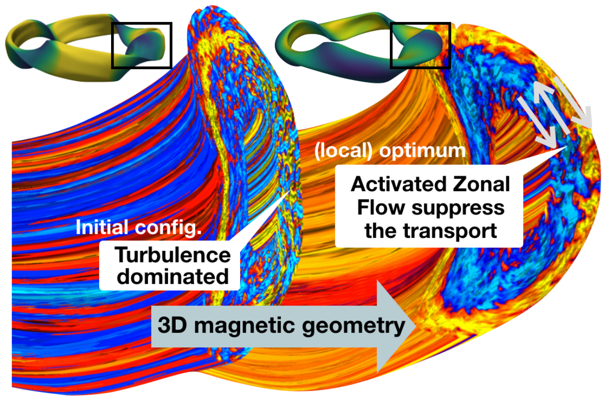

Figure 2: Nonlinear gyrokinetic simulation results of the turbulent fluctuations and zonal flows for the initial magnetic configuration(left) and a zonal-flow-activated configuration(right) found from the numerical exploration.

References

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