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Global Gyrokinetic Particle Simulations of Microturbulence in W7-X and LHD Stellarators

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With reduced neoclassical transport, turbulent transport becomes a critical issue for plasma confinement in optimized stellarators. Therefore, it is important to understand properties of microturbulence in stellarators, which is complicated by the 3D equilibrium. Furthermore, the interactions between neoclassical and turbulent transport in stellarators and the extrapolation to the reactor regime have not been widely studied by simulation or theory. The capability of simulating 3D equilibrium in GTC [1] has previously been developed and applied to simulate linear toroidal Alfvén eigenmodes in LHD [2], nonlinear microturbulence in the DIII-D tokamaks with RMP fields [3], and the effects of magnetic islands on bootstrap current [4] and on microturbulence [5]. This paper reports linear and nonlinear physics of microturbulence in LHD and W7-X stellarators from GTC simulations.

Global mode structures– GTC simulations show that the electrostatic ion temperature gradient (ITG) eigenmode structure is extended in the magnetic field direction but narrow in the perpendicular direction, and peaks at bad curvature regions in both LHD and W7-X stellarators. The eigenmode is strongly localized at the outer mid-plane in the LHD, similar to that in a tokamak. On the other hand, the eigenmode in W7-X is localized to some magnetic fieldlines or discrete locations in the poloidal plane, which is due to the mirror-like magnetic fields varying strongly in the toroidal direction that induce coupling of more toroidal n harmonics to form the linear eigenmode. The linear GTC simulation results are in reasonable agreement with results from EUTERPE simulations of the same ITG eigenmode in the W7-X using identical magnetic geometry and plasma profiles [6].

Effects of zonal flows on ITG turbulence– GTC nonlinear electrostatic simulations show that regulation by self-generated zonal flows is the dominant saturation mechanism for ITG instabilities in both LHD and W7-X. The effects of zonal flows appear to be more prominent for the W7-X than the LHD in reducing the radial correlation length and the thermal transport [6]. Furthermore, in the W7-X simulation with zonal flows, the nonlinear spectra are dominated by low-n harmonics (e.g., n=5,10,15), which can be generated both by nonlinear coupling of high-n harmonics (e.g., n=205 and n=210) and by linear toroidal coupling of these low-n harmonics with large amplitude zonal flows (n=0). Note that the linear toroidal coupling of zonal flows with non-zonal modes is induced by the 3D magnetic fields (e.g., with n=5,10,15 harmonics) in the stellarators, an interesting new physics that does not exist in the axisymmetric tokamaks.

Dynamics of zonal flows in 3D equilibrium– Zonal flow dynamics in 3D equilibria have been studied in GTC linear electrostatic simulations. In the LHD, the relaxation process of an initial zonal flow perturbation exhibits a damped GAM oscillation and a lower frequency oscillation (LFO) before reaching a steady state with a residual zonal flow. On the other hand, zonal flow damping in W7-X only exhibits the LFO oscillation. The GAM oscillation is not visible since it is strongly damped because of the small safety factor q~1.1. Our simulations show that LFO is generated mainly due to the helical magnetic inhomogeneity, consistent with existing theory that the LFO frequency is a characteristic of non-axisymmetric devices due to the presence of helically trapped particles. When the radial wavelength of the zonal flows decreases, the zonal flow residual level increases and the damping of GAM and LFO oscillations becomes stronger. Finally, the 3D magnetic fields generally enhance the GAM damping and decrease the zonal flow residual level, which is similar to that observed in GTC simulations of zonal dynamics in the DIII-D tokamak with resonant magnetic perturbations (RMP). GTC simulations using VMEC equilibrium (which preserves magnetic flux surfaces) shows that increasing the amplitude of the 3D RMP fields leads to a decrease in the residual level. Furthermore, GTC simulations using M3D-C1 equilibrium (which includes magnetic islands) show that the presence of RMP magnetic islands further enhanced GAM damping and reduce the zonal flow residual level in DIII-D RMP plasmas.

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