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Global gyrokinetic simulation of microturbulence in W7-X and LHD

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With reduced neoclassical transport, turbulent transport becomes a critical issue for the plasma confinement in optimized stellarators. Gyrokinetic simulations of turbulent transport should use global stellarator geometry to incorporate couplings of multiple toroidal harmonics, zonal flows, ambipolar electric fields, interactions between neoclassical and turbulent transport, and helically trapped particles, which drift far across flux-surfaces. In this work, global gyrokinetic particle simulations of the microturbulence are carried out in the LHD and W7-X stellarators by using the gyrokinetic toroidal code (GTC) [1].

Linear GTC simulations show that electrostatic 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 structure is localized at the outer mid-plane in the LHD, similar to that in a tokamak. On the other hand, the eigenmode structure in the W7-X is strongly localized to some magnetic fieldlines or discrete locations on 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 good agreement with results from EUTERPE simulations of the same ITG eigenmode in the W7-X using identical magnetic geometry and plasma profiles [2].

GTC nonlinear electrostatic simulations show that regulation by self-generated zonal flows is the dominant saturation mechanism for the ITG instabilities in both LHD and W7-X stellarators. Furthermore, radial width of the fluctuation intensity in both LHD and W7-X are significantly broadened from the linear phase to the nonlinear phase due to turbulence spreading. Finally, the nonlinear spectra in the W7-X are dominated by low-n harmonics (e.g., n=5,10,15), which can be generated both by nonlinear toroidal coupling of high-n harmonics (e.g., n=200 and n=205) 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 [2].

GTC simulations of zonal flow dynamics find that the relaxation process of an initial zonal flow perturbation exhibits a damped geodesic acoustic mode (GAM) oscillation and a lower frequency oscillation (LFO) before reaching a steady state in the LHD. On the other hand, the zonal flow damping in the W7-X only exhibits the LFO oscillation, which is generated mainly by the helical magnetic inhomogeneity that gives rise to helically trapped particles. The GAM oscillation is not visible since it is strongly damped due to the small safety factor q~1.1 in the W7-X. 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.

References:
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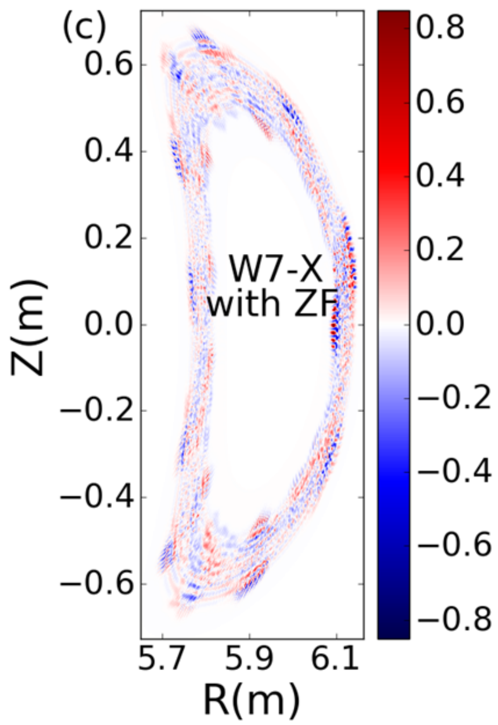

Figure 1. Poloidal contour plots of non-zonal electrostatic potential in the W7-X.