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Understanding and Predicting Profile Structure and Parametric Scaling of Intrinsic Rotation

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The main focus of this paper is on developing physical understanding and a first-principles-based model for predicting intrinsic rotation profiles in magnetic fusion experiments, including ITER. It is shown for the first time that turbulent fluctuation-driven residual stress can account for both the shape and magnitude of the observed intrinsic toroidal rotation profile. Specifically, nonlinear, global gyrokinetic simulations of DIII-D ECH plasmas indicate a substantial ITG fluctuation-induced non-diffusive momentum flux generated around a mid-radius-peaked intrinsic toroidal rotation profile. The non-diffusive momentum flux is dominated by the residual stress with a negligible contribution from the momentum pinch. The residual stress profile shows a robust anti-gradient, dipole structure in a set of ECH discharges with varying ECH power. Such interesting features of non-diffusive momentum fluxes, in connection with edge momentum sources and sinks, are found to be critical to drive the non-monotonic core rotation profiles in the experiments. Both turbulence intensity gradient and zonal flow E × B shear are identified as major contributors to the generation of the $k_{||}$-asymmetry needed for the residual stress generation. By balancing the residual stress and the momentum diffusion, a self-organized, steady-state rotation profile is calculated. The predicted core rotation profiles agree well with the experimental measurements. The radial structure of residual stress profile and associated intrinsic rotation gradient are shown to have a complicated dependence on multiple physics parameters including turbulence type, q-profile structure, and collisionality, through which possible rotation profile optimization can be developed. Interesting results obtained include intrinsic rotation reversal induced by ITG-TEM transition and intrinsic rotation profile steepening in flat-q profile regime. Fluctuation-generated poloidal Reynolds stress is also shown to significantly modify the neoclassical poloidal rotation in a way consistent with experimental observations. Finally, the first-principles-based model is applied to ITER regime, attempting to predict intrinsic rotation in electron heated burning plasmas and to illuminate its ρ_*-scaling.

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