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Role of cross-scale coupling in energetic particle transport

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Alfven eigenmodes (AE) can be excited by energetic particle (EP) pressure gradients and can drive a large EP transport that degrades tokamak plasma confinement. Despite the separation in the spatial and temporal scales, there can be strong coupling between AE and microturbulence. Zonal flows can be nonlinearly generated by, and in turn, suppress both the AE and microturbulence. Microturbulence can damp the zonal flows and zonal structures generated by the AE. EP scattering by the microturbulence can affect phase space dynamics in nonlinear AE-EP interactions. There can also be direct mode-mode coupling between AE and driftwave eigenmode. Understanding these cross-scale interactions requires global integrated simulations incorporating multiple physical processes in a complex toroidal geometry and treating all particle species on an equal footing.

In this work, the cross-scale coupling between AE and microturbulence is studied in global integrated simulations by the gyrokinetic toroidal code (GTC) with comprehensive electromagnetic physics using gyrokinetic thermal and fast ions and drift kinetic electrons. Global gyrokinetic simulations of recent critical gradient DIII-D tokamak experiments find that reversed shear Alfven eigenmodes (RSAE) excited by energetic ions from neutral beam injection can saturate by self-generated zonal flows. However, saturated RSAE amplitude and EP transport are an order of magnitude higher than the experimental observations when the microturbulence is artificially suppressed. In contrast, in the realistic simulations coupling micro-meso scales, the saturated RSAE amplitude and EP transport are greatly reduced to the experimental level due to both zonal flow shearing and EP scattering by the ion temperature gradient (ITG) turbulence. The dominant RSAE mode structure and amplitude from the cross-scale gyrokinetic simulations agree well with experimental measurements using electron cyclotron emission (ECE) [Liu et al, Phys. Rev. Lett. 128, 185001 (2022)]. The EP radial scattering by the microturbulence is much more important than Coulomb collisions in destroying coherent structures in the EP phase space to maintain a steady state RSAE turbulence.

Extrapolations from DIII-D to the ITER experiments will be discussed. In this project, EP confinement properties of the ITER operation scenarios have been comprehensively assessed using global gyrokinetic codes (GTC, CGYRO, ORB5), kinetic-MHD codes (FAR3D, GAM-solver, M3D-C1, MEGA, NOVA-C, XTOR-K), and reduced EP transport models (Kick, RBQ, TGLF-EP). These codes have been first verified and validated for simulations of EP transport in the DIII-D experiments. This collaborative research has been selected for US DOE FY2022 Theory Performance Target and adapted as the ITPA energetic particle joint activity B.11.12 project.

These large scale simulations find that macroscopic fishbone can be unstable in the ITER baseline scenario, but saturate at a low amplitude with insignificant distortion of flux surface and EP re-distribution. Various meso-scale Alfven eigenmodes (AE) saturate at high amplitudes and drive a large EP transport in the ITER steady state scenario, which results in a modest flattening of the EP profiles during the short simulation time. Strong microturbulence drives directly little EP transport but large thermal transport in both scenarios, which could affect EP transport driven by the AE and fishbone. These studies point to a modestly optimistic assessment of the EP confinement in the ITER, but also a significant relaxation of the alpha particle profile in the steady state scenario. Finally, integrated simulation of cross-scale coupling is needed to reliably predict EP confinement in the ITER, as demonstrated in the simulations of the DIII-D experiments.