4th Asia-Pacific Conference on Plasma Physics, 26-31Oct, 2020, Remote e-conference

Total-f gyrokinetic simulation of turbulence-RMP interaction in realistic diverted edge geometry

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The many kinetic side effects of RMPs complicate reliable prediction of the effectiveness of RMP ELM control in ITER. For example, plasma density is reduced (by up to 50% [1]), which can lower the fusion efficiency in ITER, while the electron temperature pedestal is preserved or becomes even somewhat steeper. This has been a puzzle in experimental observation [1] and transport modeling [2] but is now qualitatively reproduced by gyrokinetic total-f simulations of the plasma transport driven by n=3 resonant magnetic perturbations (RMPs) in a DIII-D H-mode plasma performed with the gyrokinetic code XGC [3,4].

XGC calculates collisional (neoclassical) and turbulent transport self-consistently in realistic divertor geometry with gyrokinetic ions and drift-kinetic electrons, nonlinear Fokker-Planck collisions, and neutral particle recycling. The RMP field – calculated using linear extended MHD simulation with the M3D-C1 code and coupled into the electrostatic version XGC – is stochastic around the pedestal foot (ψ_N>0.98) but contains good KAM surfaces between pedestal foot and top.

In the pedestal foot, collisional transport is enhanced and responsible for the bulk of particle transport. Around the shoulder and midpoint of the pedestal, enhanced turbulent particle transport from trapped electron modes takes over. The increase of turbulent transport is at least partly consistent with RMP-induced weakening of the ambipolar radial electric field and is caused by increased cross-power between the electrostatic potential and density fluctuations rather than a change in the cross-phase. The electron heat transport barrier midway down the pedestal is preserved with the electron heat conductivity being completely suppressed in the steepest part of the pedestal, making the electron energy loss totally convective flowing out together with the density. This is illustrated in Fig. 1, which shows the contributions of turbulence modes with $0 \le k_\theta \varrho_i \lesssim 1$, ($k_\theta$ is the poloidal wavenumber and ϱ_i is the ion gyroradius) to the particle and electron energy and heat flux Γ, Q_e, and $q_e = Q_e\text{-}5/2\, k_B T_e \Gamma$. While both, particle and energy flux increase with RMPs, the heat flux is suppressed due to a cancellation between outward heat flux at longer wavelength ($k_\theta \varrho_i \lesssim 0.3$) and inward heat flux at shorter wavelength ($k_\theta \varrho_i \gtrsim 0.3$).

The collisional component of the electron heat flux, while significantly enhanced in the outer thin stochastic layer, remains small compared to the turbulent heat flux, indicating that this thin stochastic region near the separatrix is not stochastic enough for Rechester-Rosenbluth transport theory to be applicable. The comparison between experiment and XGC simulation will be extended from DIII-D by short (~0.2 ms) gyrokinetic simulations of a KSTAR H-mode discharge with n=1 RMPs. Extension of our studies to ITER is planned.

Funding is provided by the U.S. DOE under contracts DE-AC02-09CH11466 (PPPL) and DE-FC02-04ER54698 (DIII-D). Computing time is provided via INCITE at ALCF (DE-AC02-06CH11357) and ERCAP at NERSC (DE-AC02-05CH11231).

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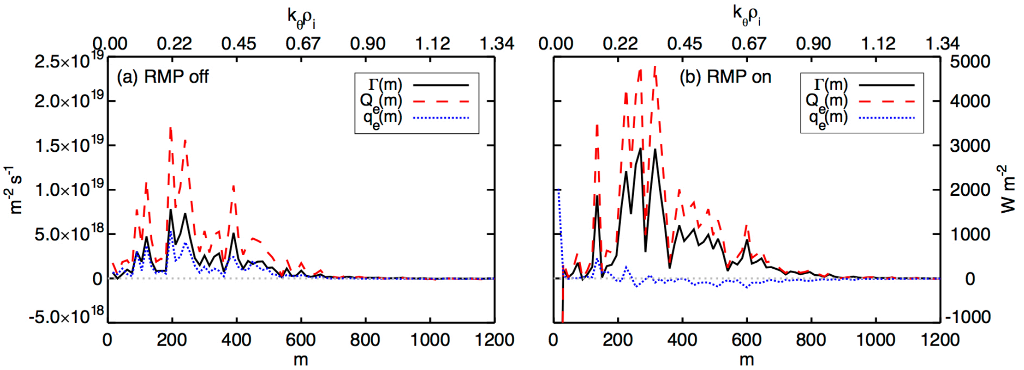

Fig. 1: Contributions to particle flux Γ, electron energy flux Q_e and electron heat flux q_e vs. poloidal mode number m and $k_\theta\rho_i$ at normalized poloidal flux ψ_N=0.97.