Optimal flux balance and steady burning state in multi-ion turbulent plasmas

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Turbulent transport driven by various inhomogeneities in plasmas is an essential physical process to govern the confinement performance in magnetically confined fusion reactors. Many theoretical and numerical efforts have been devoted to study the turbulence dynamics and transport properties in the single-ion-species plasma, based on gyrokinetic formalisms.

In fact, burning plasmas are intrinsically composed of multiple ion species such as Deuterium(D) and Tritium(T), the high-energy α particles produced by the fusion reaction, the thermalized Helium(He)-ash, and high-Z impurities resulting from the plasma-facing materials. More complex turbulent transport processes are, thus, expected in the burning plasmas, compared to those in the single or very few ion-species plasmas, which are usually addressed in experiments. Particularly, the optimal flux balance in the particle and thermal transport to sustain the steady burning state remained to be unrevealed.

In this study, ion temperature gradient (ITG) and trapped electron modes (TEM) driven turbulent transport in an ITER-like tokamak plasma is investigated in terms of multi-species gyrokinetic Vlasov simulations[e.g., Refs. 1, 2] with Deuterium(D), Tritium(T), Helium(He), and real-mass kinetic electrons including their inter-species particle collisions[Fig. 1]. Beyond the conventional zero-dimensional power balance analysis presuming the global energy and particle confinement times, gyrokinetic-simulation-based analysis of a steady burning condition, with He-ash exhaust and D-T fuel inward transport is demonstrated. It is clarified by comprehensive numerical scans that a significant imbalance appears in the turbulent particle flux for the fuel ions of D and T, depending on the background D-T density ratio and the He-ash accumulation rate[3]. We also found more pronounced imbalance between D- and T-particle fluxes in the case with the finite He-ash accumulation.

Furthermore the several optimal profile regimes to satisfy Reiter's steady burning condition given by $\tau_{\mathrm{He}} < \alpha^* \tau_{\mathrm{E}}$[4] are identified by the gyrokinetic turbulence simulation[Fig. 2], where $\alpha^* \sim 7 - 15$ denotes the constant depending on the wall and pumping condition. Also, the impacts of zonal-flow generation, nonthermal He-ash accumulation[5], and the magnetic geometry on the flux balance and the optimal profile regimes are clarified.

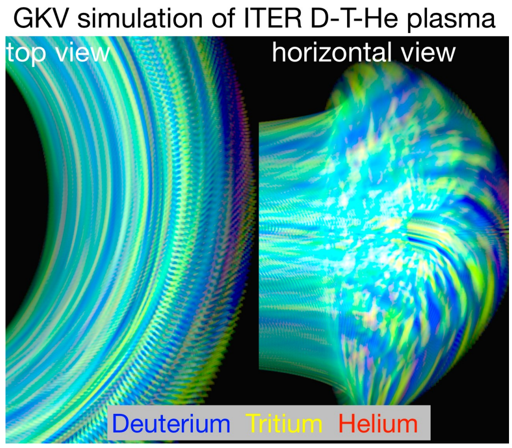

Figure 1: Turbulent fluctuations of D(blue), T(yellow), and He(red) in multi-species ITG-TEM turbulence.

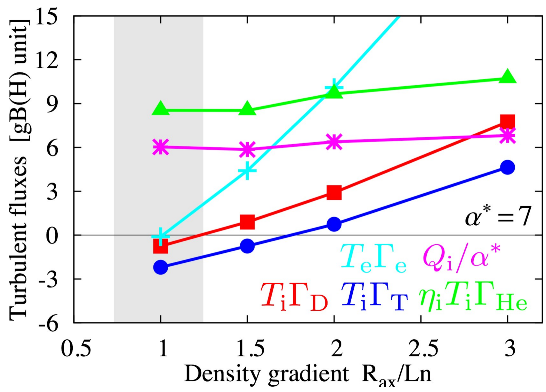

Figure 2: Density-gradient scan of particle and energy fluxes, where the steady burning condition is satisfied in $R_{ax}/L_n \lesssim 1.27$(dashed-line).

References

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