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Saturation of fishbone instability through zonal flows driven by energetic particle transport in tokamak plasmas

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Gyrokinetic and kinetic-MHD simulations are performed for the fishbone instability [1,2] based on the DIII-D discharge #178631, chosen for validation of first-principles simulations to predict the energetic particle (EP) transport in an ITER pre-fusion baseline scenario. Fishbone modes are found to generate zonal flows, which dominate the fishbone saturation [3]. The underlying mechanisms of the two-way fishbone-zonal flows nonlinear interplay are discussed in details [4]. Numerical and analytical analyses identify the fishbone-induced EP redistribution as the dominant generation mechanism for zonal flows. The zonal flows modify the nonlinear dynamics of phase space zonal structures, which reduces the amount of EPs able to resonate with the mode, leading to an early fishbone saturation. Simulation results including zonal flows agree quantitatively with DIII-D experimental measurements of the fishbone saturation amplitude and EP transport, supporting this novel saturation mechanism by self-generated zonal flows. Moreover, the wave-particle mode-locking mechanism is shown to determine quantitatively the fishbone frequency down-chirping, as evident in GTC simulation results in agreement with predictions from analytical theory. Finally, the fishbone-induced zonal flows are possibly responsible for the formation of an ion-ITB [5] in the DIII-D discharge. Based on the low EP transport and the large zonal flow shearing rates associated with the fishbone instability in gyrokinetic simulations of the ITER scenario, it is conjectured that high performance scenarios could be designed in ITER burning plasmas through fishbone-induced ITBs.

References

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