Two Distinguished Processes of Zonal Flow Generation in Tokamak Plasmas

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We study zonal flow generation mechanisms and resulting turbulence saturation levels in global gyrokinetic ion-temperature-gradient turbulence by using the gKPSP code [1]. To examine zonal flows in various scales, we perform a series simulations varying the width of the strong temperature gradient region W. A numerical analysis of potential vorticity (PV) transport [2] enables us to quantitatively address this highly nonlinear problem, which is formidable to track analytically.

We identify two distinguished regimes of zonal flow generation. The radial structure of a zonal flow is a key factor determining the regimes. The zonal flow structure results from interference of the radial waveforms of PV flux spectral components, which is governed by the corresponding modes of a turbulence spectrum.

With a broad unstable region, a large structure of a zonal flow is initiated by radially distributed waveforms of the PV flux spectrum, which span different parts of the zonal flow. During the build-up of the zonal flow, the turbulence spectrum undergoes a gradual self-regulation process. Accordingly, the zonal flow structure changes in a time scale of turbulence correlation. This incoherent zonal flow cannot be subjected to the familiar modulational instability. At the turbulence saturation time, a fine-scale zonal flow emerges. We uncover that the fine-scale zonal flow results from the radially aligned waveforms of the PV flux spectrum caused by phase synchronization of poloidal harmonics of density perturbations. The generation of the zonal flow is decelerated, compared to the linear stage, due to the slowing-down of turbulence growth. The phase synchronization compensate for the reduction in zonal flow generation.

With a narrow unstable region, radial waveforms of the PV flux spectrum are not allowed to separate and be misalign with each other. Constructive interference of the waveforms of the PV flux spectrum induces a large and coherent total PV flux from the zonal flow onset time. The dominant $E \times B$ nonlinearity of the coherent zonal flow leads to the familiar modulational instability of the zonal flow. Thanks to the efficient zonal flow generation, turbulence is promptly saturated at the level lower than that in the broad W cases.

This finding is consistent with the previous work showing the turbulence reduction with the finite width of the strong driving region [3]. We suggests that the two different physics mechanisms of zonal flow generation is, at least partly, attributed to the system size effects of global gyrokinetic ion-scale turbulence.

References

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