9th Asia-Pacific Conference on Plasma Physics, 21-26 Sep, 2025 at Fukuoka

Drift wave soliton formation via zonal flow generation and implication on staircase formation

Ningfei Chen
Max-Planck Institute for Plasma Physics, Garching 85748, Germany
E-mail: ningfei.chen@ipp.mpg.de

Understanding the triggering and regulation mechanisms of anomalous transport is a significant issue for magnetically confined plasmas. Drift waves (DWs) turbulences [1], driven by plasma pressure gradient intrinsic to confined plasmas, are considered as important candidates for inducing anomalous transport. Numerical simulations have found that zonal flow (ZF) generated by DWs can significantly reduce turbulence amplitude and associated transport [2]. There are two routes toward nonlinear generation of ZF by DW, i.e., spontaneous excitation and beat-driven mechanisms. The first is spontaneous excitation of ZF via modulational instability [3], which requires the DW intensity to exceed a threshold and also incorporates scattering of DWs into a short-wavelength stable domain, leading to self-regulation and saturation of DW turbulence. The other is thresholdless ZF beat-driven excitation [4-6], with the growth rate of ZF being twice the instantaneous growth rate of the DWs. DW soliton formation due to ZF generation is identified for both channels for ZF excitation [7, 8], resulting from balancing kinetic dispersiveness and nonlinear ZF trapping, which potentially contribute to nonlocal transport and confinement degradation.

In this work, a paradigm model of ZF generation by DWs is investigated using nonlinear gyrokinetic theory, with both beat-driven and spontaneous excitation of ZF taken into account on the same footing. It is found that spontaneously excited ZF exhibits dual role in DW nonlinear dynamics, i.e., repulsive nonlinearity enables micro-barriers formation and attractive nonlinearity enables soliton formation. This is embedded in the structure of Reynolds stress and the zero-frequency nature of ZF. While, beat-driven ZF always contributes to attractive nonlinearity. This fact reveals that, apart from the amplitude of ZF, the radial mode structure of ZF is also an important element for nonlinear DW dynamics. As a result, DW solitons can be confined within neighboring micro-barriers generated by spontaneously excited ZF, which can serve as a potential explanation to the staircase structures observed in simulations.

References

[1] Horton W., Rev. Mod. Phys. 71, 735 (1999).
[2] Lin Z., Hahm T., Lee W., Tang W., and White R., Science 281, 1835 (1998).
[3] Chen L., Lin Z., and White R., Phys. Plasmas 7, 3129 (2000).
[4] Dong G., Bao J., Bhattacharjee A., and Lin Z., Phys. Plasmas 26, 010701 (2019).
[5] Wang H., Holod I., Lin Z., Bao J., Fu J., Liu P., Nicolau J., Spong D., and Xiao Y., Phys. Plasmas 27, 082305 (2020).
[6] Todo Y., Berk H., and Breizman B., Nucl. Fusion 50, 084016 (2010).
[7] Guo Z., Chen L., and Zonca F., Phys. Rev. Lett. 103, 055002 (2009).
[8] Chen N., Chen L., Zonca F., and Qiu Z., Phys. Plasmas 31, 042307 (2024).