Nonlinear Saturation of Kinetic Ballooning Modes by Zonal fields in Toroidal Plasmas

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Kinetic ballooning modes (KBM) are widely believed to play a critical role in disruptive dynamics as well as turbulent transport in tokamaks [1]. While the nonlinear evolution of ballooning modes has been proposed as a mechanism for detonation [2] in tokamak plasmas, the role of kinetic effects in such nonlinear dynamics remains largely unexplored. Numerical simulations on the nonlinear saturation of KBMs have not been conclusive [3-5]. Various simulation results suggest that KBMs can only saturate nonlinearly with pressure profile relaxation [4] or increased flow shear [5] above a critical beta. In this work, gyrokinetic particle-in-cell simulation results of nonlinear KBM, which include the effect of parallel magnetic field fluctuations [6], are presented for the cyclone base case. We find that instead of detonating, the nonlinear KBM continues to grow exponentially in an "intermediate" regime [7], followed by nonlinear saturation regulated by spontaneously generated zonal fields that appear to be significantly larger than seen in earlier KBM simulations [3]. The origin of the zonal fields can be attributed to three-wave coupling processes. In the intermediate nonlinear regime, thin and localized current sheets develop that are prone to secondary tearing instabilities, but the growth rate of these reconnecting instabilities appear to be subdominant to KBM growth at significant values of beta. Qualitative implications of these results for tokamaks as well as substorm onset in the Earth's magnetotail will be discussed.

[1] P. B. Snyder et al., Phys. Plasmas, 16, 056118 (2009)

[2] S. Cowley and M. Artun, Phys. Reports, 283, 185 (1997)

[3] A. Ishizawa et al., J. Plasma Physics, 81, 435810203 (2015)

[4] C. Ma and X. Xu, Nucl. Fusion, 57, 016002 (2016)

[5] R. E. Waltz, Phys. Plasmas, 17, 072501 (2010)

[6] G. Dong et al., Phys. Plasmas, 24, 081205 (2017)

[7] P. Zhu, A. Bhattacharjee, and K. Germaschewski, Phys. Rev. Lett., 96, 065001 (2006)