$\boldsymbol{E \times B}$ staircase-like pattern formation in gyrokinetic simulations: a comparison with experiment and reduced models

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Global pattern formation is commonly observed in complex nonlinear and non-equilibrium systems, such as lateral belts in planetary atmospheres[1], potential vorticity (PV) staircase in geophysics[2], stratified fluids[3], etc.. In magnetic confined fusion plasmas, study of $\boldsymbol{E \times B}$ staircase-like pattern formation has become a prominent subject[4]. It is well understood that the zonal component of $\boldsymbol{E \times B}$ flow with zero toroidal and poloidal wave number ($m = n = 0$) develops from the drift wave turbulence-zonal flow system. The global structure of zonal flow has significant effects in the regulation of transport. Investigations have shown the capability of zonal flow staircase in the formation of transport barriers, which can constrain the turbulent transport and avalanches, and therefore improve the energy confinement in fusion plasmas.

We will present a brief background[5-10] followed by new outcomes of the research efforts in zonal flow staircase with a focus on the following two aspects. Firstly, the existence and effects of zonal flow staircase are demonstrated from both gyrokinetic simulations[11] and experimental measurements[12]. This includes validations of high spatial resolution experimental measurements of electron temperature profiles of KSTAR plasmas and direct gKPSP[13] gyrokinetic numerical experiments with experimental profiles as inputs (Fig. 1). Secondly, the predictions from reduced analytic models[14-17] which are necessary for physics mechanism identification, are critically examined against the gyrokinetic simulation results[18]. For example, the escalation of the staircase predicted by a reduced model based on Hasegawa-Wakatani system of equations has also been observed in gyrokinetic simulations (Fig. 2) and key parametric dependencies will be compared. Relative merits of the reduced theory with a boundary value approach and an initial value approach[19] in the formation of staircase will be addressed from the view point of gyrokinetic simulations. Finally, remaining conundrums, challenges and future work in the investigation of the global pattern formation will also be discussed.

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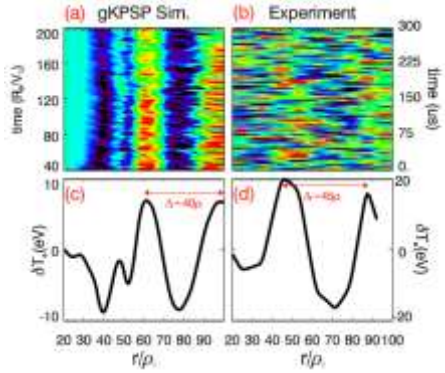

Figure 1: Electron temperature profile corrugations from gKPSP numerical simulation (left) and KSTAR experiment (right).

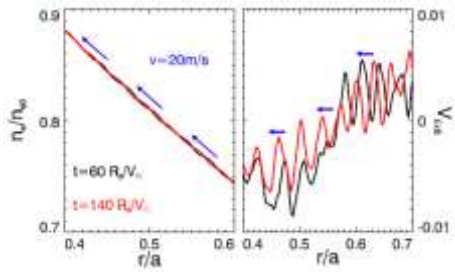

Figure 2: Upward escalation of staircases in density (left) and zonal flow (right) profiles from gKPSP simulations