Impact of ion parallel flow dynamics on the radial zonal flow pattern formation

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The physics of turbulence-zonal flow interaction is a well-established paradigm explaining many aspects of turbulent transport and subsequent profile formation in magnetically confined plasmas. A remaining fundamental question is how the radial pattern of zonal flow is determined for given fluctuations sources (i.e. plasma equilibrium) and boundary conditions. This likely involves an intricate physical process, which can be generally categorized as a nonlinear radial wave number selection problem. A conventional theoretical approach to this problem is the modulational instability or some variations of it. In this work, we study the impact of parallel ion dynamics, i.e. parallel compressions and Reynolds stress on the radial zonal flow pattern formation. We address the problem through three different nonlinear simulations: (1) the coupled Hasegawa-Mima and parallel flow dynamics, (2) the global fluid ITG simulations, and (3) the global δf gyrokinetic ITG simulations. Results show a significant impact of the parallel velocity fluctuations and the equilibrium parallel velocity gradient on the radial pattern of zonal flow. When parallel velocity shear is large enough, the fluid ITG simulation shows the onset of parallel velocity gradient (PVG) instability. This leads to the restoration of the ion temperature profile stiffness and the Dimits shift due to the generation of bifurcation-like strong ZF by parallel velocity fluctuations. Gyrokinetic simulations show that ZF pattern can be understood through the potential vorticity (PV) transport in toroidal ITG turbulence. The importance of potential vorticity flux in determining zonal flow generation is demonstrated all the models employed. All these observations suggest the intricate coupling of parallel and perpendicular dynamics. Implications on these findings and remaining issues will be discussed at the conference.