Disappearance of Dimits Shift in Realistic Fusion Reactor Plasmas with Negative Magnetic Shear

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Turbulent transport driven by drift wave instabilities is widely observed in fusion plasmas. One of the common causes of ion turbulent transport in tokamaks is the Ion Temperature Gradient (ITG) instability, which significantly reduces the efficiency of fusion reactors. The profile stiffness propels fusion plasmas toward marginal stability, resulting in the plasma temperature being determined by the critical temperature gradient. Consequently, even a slight elevation of the critical temperature could yield a remarkable increase in fusion power.

The axisymmetric $E \times B$ rotation or zonal flow, self-consistently generated by turbulence, is generally accepted as a regulator of the saturation level of turbulent transport in fusion plasmas. Near the marginal stability, the zonal flow has been observed to completely suppress turbulence and transport, causing a nonlinear up-shift of the critical temperature gradient for ITG, known as the Dimits shift. Despite its significance in understanding crucial dynamics in fusion plasmas, such as zonal flow-turbulence interaction and L-H transition, the physics mechanisms underlying the Dimits shift remain largely elusive

Magnetic shear is another crucial factor that can regulate turbulence in fusion plasmas. Experimental and simulation analyses have shown that reverse magnetic shear significantly affects particle and heat transport in toroidal plasmas through suppression of linear instabilities.

In this study, we employ global GTC (Gyrokinetic Toroidal Code) simulations to investigate ITG turbulent transport using plasma parameters based on the design of the CFETR (China Fusion Engineering Experimental Test Reactor) featuring reverse magnetic shear, aiming to investigate the nonlinear interaction between turbulence, zonal flow and magnetic shear. The weak negative magnetic shear is observed to be more stable for the ITG instability than strong positive shear in this equilibrium configuration, primarily stemming from the scarcity of mode rational surfaces induced by the weak negative shear. This superiority in suppression for the negative shear persists in nonlinear turbulence with zonal flow artificially eliminated, where the emergence of turbulence solitons is observed and found associated with locally dense mode rational surfaces. However, the difference in transport levels among different magnetic shears diminishes in the presence of self-consistently generated zonal flow, accompanied by the disappearance of turbulence solitons. The zonal flow is found to originated from a force driven process by the primary instability, instead of the conventional modulational instability. The nonlinear generation of zonal flow is found to be significantly affected by the magnetic shear. The study further reveals a remarkable phenomenon that the Dimits shift no longer exists for negative magnetic shear, which are attributed to the weakness of the zonal flow generation near the ITG marginal stability.