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

On collisionless saturation of zonal flow shear in ITG turbulence: Implications for negative triangularity.

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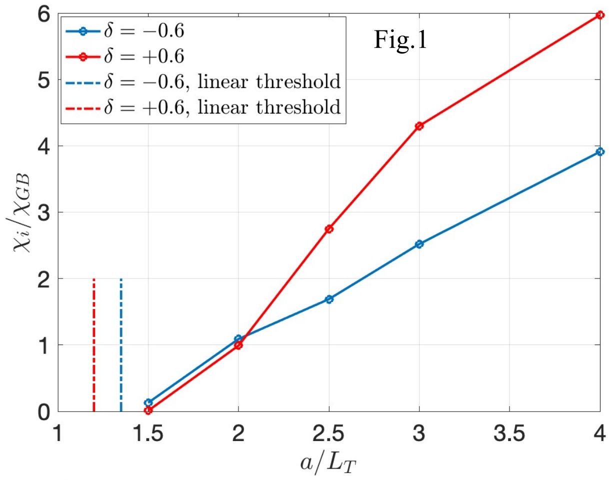
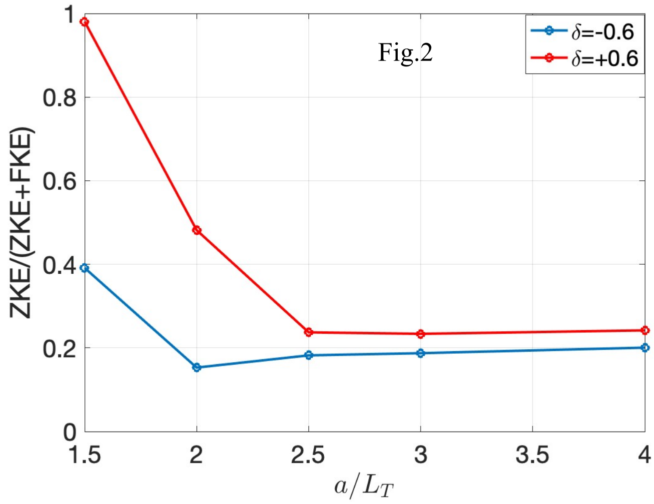
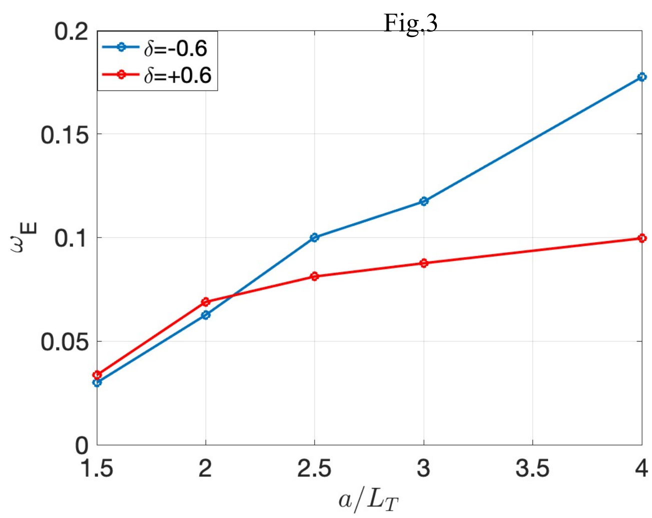
Zonal flow shear is well-known to mitigate and regulate drift-wave turbulence and transport. However, the zonal flow saturation mechanism in the collisionless regime remains poorly understood. The frequently invoked linear Kelvin-Helmholtz (K-H)-like tertiary instability of zonal shear is questionable in evolved turbulent systems. Using gyrokinetic simulations, we investigate zonal entropy transfer to better understand the strength and lifetime of zonal flow shear. Time series of the zonal entropy transfer function reveal intermittent excursions to negative values, indicating bursts of back-transfer of energy from zonal modes to fluctuations. The lifetime of zonal shear, as measured by the auto-correlation time, correlates with the fraction of time during which the entropy transfer rate is negative. This back-transfer, quantified by the negative fraction of the zonal entropy transfer rate, increases with the temperature gradient. Consequently the zonal shear lifetime is shorter at higher temperature gradients. Near marginal stability, the back-transfer fraction is significantly reduced, leading to a pronounced increase in zonal flow coherence. These findings provide new insights into the dynamics of the Dimits shift regime and the mechanisms underlying improved confinement observed in negative triangularity (NT) tokamaks.

The mitigation of ITG turbulence and transport by negative triangularity[1] is linked to the extended lifetime and increased strength of the zonal flow shear, resulting from a reduced fraction of back-transfer of energy from zonal flow shear to fluctuations. At lower temperature gradients near marginality , the difference in turbulent heat diffusivities for PT and NT diminishes. Note that the nonlinear critical temperature gradient is similar for both PT and NT configurations, even though the linear critical gradient is higher for NT. Consequently, the Dimits shift is higher for PT than for NT, as shown in Fig.1.





The partitioning of energy between zonal flows and turbulent fluctuations is analyzed as a function of both temperature gradient and triangularity. The ratio of zonal kinetic energy (ZKE) to the total kinetic energy (ZKE + fluctuation kinetic energy, FKE) shows only weak dependence on the temperature gradient far from marginality, but rises sharply as the system approaches marginality from above. At all temperature gradients, this zonal kinetic energy fraction remains consistently higher for PT than for NT, as shown in Fig.2. On the other hand, the zero-frequency zonal E×B shearing rate decreases with decreasing temperature gradient. Away from marginality, the shearing rate is higher for NT than for PT, but the two converge near marginality [Fig.3]. Interestingly, NT plasmas exhibit lower ZKE but higher zonal E×B shearing rates, whereas PT plasmas show the opposite trend—higher ZKE but lower zonal ExB shear.



This work is supported by US DOE award number DE-FG02-04ER54738.

References

[1] Rameswar Singh, P H Diamond and A Marinoni, Nuclear Fusion 2024 **65** 026016