Physics of ITG transport reduction in negative triangularity plasmas

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Negative triangularity (NT) plasmas offer attractive enhanced confinement compared to positive triangularity (PT), without the the undesirable 'side effects' of Edge Transport Barriers, such as those in H-mode[1]. Here, we show that the enhanced confinement in NT plasmas is linked to the presence of stronger and more coherent zonal ExB shear.

Understanding of enhanced confinement in NT is still developing, and theory and modeling have yet to address the important regime of ITG-driven transport. Here, we show that NT shaping mitigates ITG transport by enhancing the persistence (i.e autocorrelation time) and strength of self-generated zonal flow shears[2]. Collisionless gyrokinetic simulations were used to scan the turbulence properties and the values of χ_i/χ_{GB} over a range of triangularity δ with $\delta > 0$ and $\delta < 0$. Here, χ_i is the measured turbulent thermal diffusivity and χ_{GB} is the gyro-Bohm value. Fig(1) shows that the coherence of zonal shear is markedly extended in NT, while Fig(2) shows that χ_i/χ_{GB} drops concomitantly.

Analysis of natural figures of merit (FOM), namely $\left\langle\omega_E^2\right\rangle^{1/2}\tau_c$ and $\left\langle\omega_E^2\right\rangle^{1/2}\gamma^{-1}$, indicates that the FOM increase

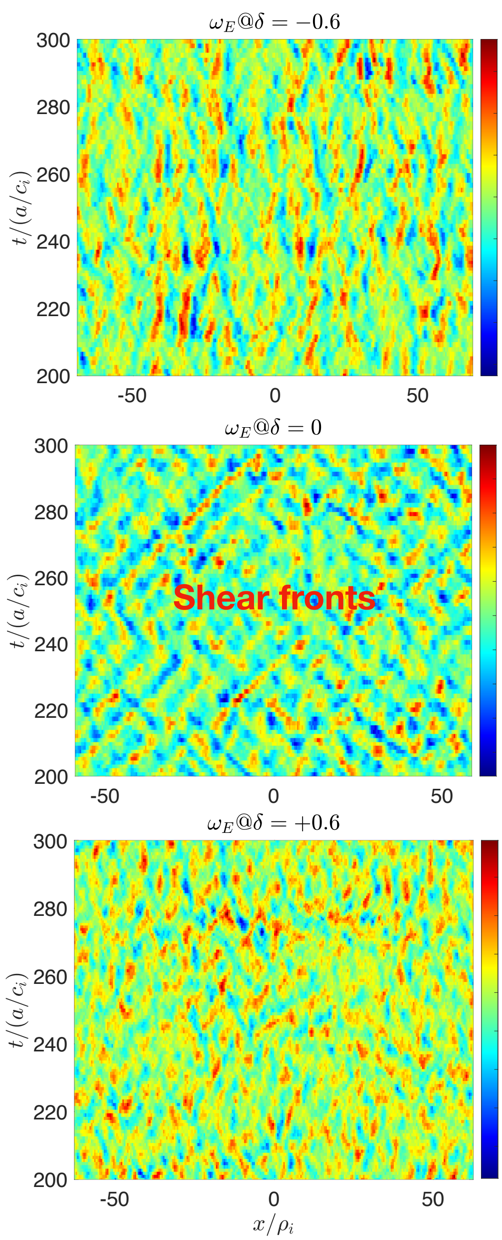

Fig1: Comparison of shearing field evolution for NT, circular and PT shapes. Note shear front propagation for circular case.

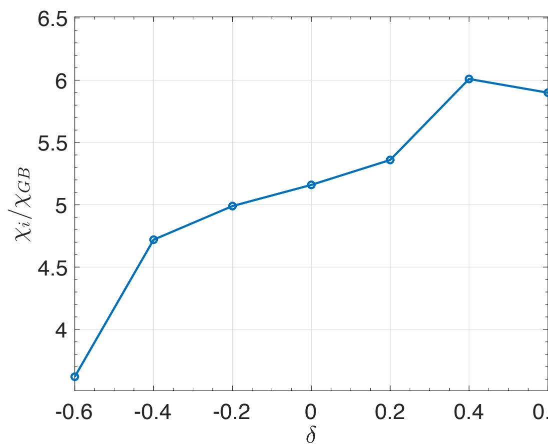

Fig2: Turbulent heat diffusivity drops for NT, as opposed to PT.

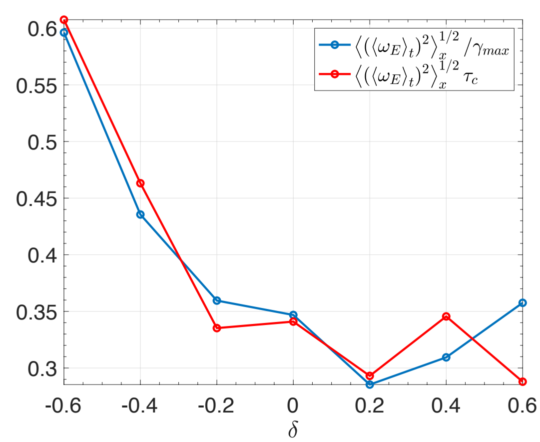

Fig3: FOM of shear suppression with triangularity.

strongly for NT, as shown in Fig3. Here, $\left\langle \omega_E^2 \right\rangle^{1/2}$ is the RMS shearing rate, τ_c is the turbulence auto-correlation time and γ is the linear growth rate.

Simulations utilize the GENE code with a local Miller equilibrium to study collisionless ITG turbulence with adiabatic electrons. Meaningful comparisons are enabled by scanning δ values for fixed kinetic profiles. Linear growth rates are smaller in NT, due to a reduced eigenfunction-averaged drift frequency and a wider region of stronger local negative magnetic shear near the outboard mid-plane (cf Fig4). The normalized thermal diffusivity is lower for $\delta < 0$ than for $\delta > 0$, as shown in Fig2, due to reduced radial correlation length and increased auto-correlation time of fluctuations. The fluctuation levels are lower in NT, while values of the cross-phases remain comparable to their $\delta > 0$ values. ExB zonal shears are stronger for NT than PT. The dimensionless shearing FOM is much larger for NT(cf Fig3), while the zonal shear coherence is much more persistent, too (cf Fig1). Turbulence generated T_i corrugations are typically weaker than the mean ∇T_i. Nevertheless, corrugations are more pronounced for NT than for PT.

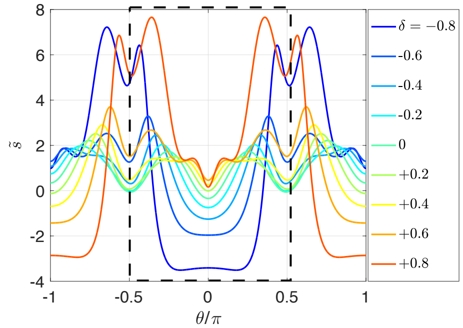

Fig4: Manifestation of reversed local shear at the outboard mid-plane for NT

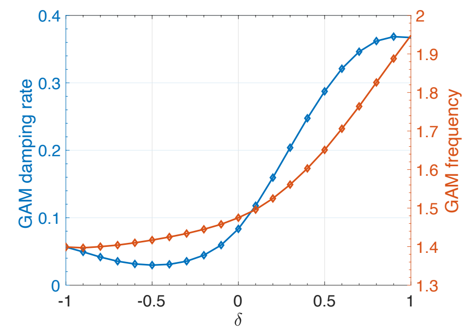

Fig5: GAM frequency and collisionless Landau damping rates are reduced for NT.

Simulations[3] also show that the Geodesic Acoustic Mode (GAM) frequency decreases with decreasing δ, such that the frequency is lower for $\delta < 0$ compared to that for $\delta > 0$. This again implies stronger spatiotemporal coherence of the shearing field in NT, than in PT. Analytic gyrokinetic calculations reveal that the reduction in frequency for $\delta < 0$ is due to reduction in both radial drift frequency and the parallel transit frequency. The GAM Landau damping rate is is also found to be lower for $\delta < 0$ as compared to that for $\delta > 0$. Notice that the damping rate is reduced much more strongly (~7 times) than the real frequency, as PT $\rightarrow$NT. This can be seen in Fig5. This implies a stronger shearing field for fixed drive in NT. Energy partition with δ between GAM and zonal shear is being explored.

Several other aspects of these results are of interest. i) Zonal shearing fronts are observed to propagate. These could be detectible in experiments. ii) The R-H residual calculation predicts weaker zonal potential for NT[4], yet the measured simulation zonal shears are, in fact, stronger for NT. This is due to detailed space-time microstructure of the shearing field. The result illustrates the pitfalls of using linear response theory to calculate the zonal shears. iii) The predicted FOM δ-dependence is experimentally testable. iv) We speculate that the enhanced zonal flow coherence time may be due to the broader region of negative magnetic shear in NT. This feature could act to limit ZF instability and energy re-coupling to the fluctuation field. Thus, the magnetic structure appears to enhance the beneficial effects of ExB shear. v) We also speculate that these results are relevant to TEM turbulence, though additional effects via the trapped particle population will likely enter.

These results further highlight the potential of high-zonal-shear-dominated negative triangularity plasmas as promising candidates for fusion reactors. Ongoing work seeks to explore and illuminate i) - v) above and to develop pathways to validation of the emerging model.

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