Interactions of Stable Modes and Zonal Flows in ITG Turbulence

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Abstract:
The regulation of ion temperature gradient (ITG) turbulence by zonal flows, which reduces turbulence levels and transport, is shown to involve enhanced energy transfer from the instability to damped modes in the low wavenumber range of the instability, with zonal flows acting as a catalyst. Energy transfer is dominated by the nonlinear triplet interaction of the unstable mode, a zonal flow, and stable modes at three interacting perpendicular wavenumbers. This holds for both fluid and gyrokinetic models. In the former a highly efficient transfer, enabled by minimization of the nonlinear three-wave frequency sum, a large coupling coefficient, and large zonal flow amplitude, allow saturation at a much lower level than possible when zonal flows are removed and energy transfer to damped modes is less efficient. Zonal flow shearing is not an important aspect of this process. The interaction of the unstable mode and zonal flows excites damped modes with tearing parity. At finite beta, these make the magnetic field stochastic and drive magnetic fluctuation-induced electron thermal transport. Because the tearing component is excited through coupling with zonal flows, zonal flows have the heterodox property of enhancing transport, albeit in the electron channel through magnetic stochasticity. In the main ion thermal transport channel damped modes reduce transport levels relative to quasilinear theory. In gyrokinetic simulations of ITG turbulence, stronger damped mode excitation, leading to a larger ratio of quasilinear heat flux to true flux, occurs for weaker magnetic shear. This ratio also increases in Tore Supra at weak magnetic shear, and is associated with stronger zonal flow excitation, consistent with the interaction of damped modes and zonal flows.

1 Introduction

Zonal flows cause a large reduction in ion temperature gradient (ITG) turbulence and transport. The mechanism has been widely attributed to the shearing of ITG turbulence by zonal flows. Moreover, because zonal flows do not directly contribute to transport-flux correlations, their role in turbulence and transport was seen as only beneficial.

In parallel with but unconnected to the development of the zonal flow paradigm [1], there has been a growing realization that instability driven turbulence does not saturate
by a cascade to collision dominated small scales, but by nonlinear energy transfer to
damped modes at the scales of the instability [2]. This process is robust - the nonlinear
transfer is efficient, going in a parallel fashion to multiple damped modes, in contrast
to the serial cascade process that takes energy from large scale to small, collisionally
dissipated scales. In gyrokinetics the number of damped modes is very large, limited
only by numerical resolution. Damped modes affect saturation dynamics provided their
damping rate is not large compared to the growth rate of the instability [3]. The process is
also very general, having been observed in virtually every instability model that requires
more than a single field [4]. As a result of these effects, removing instability energy access
to damped modes, and thereby forcing a system to saturate by the less efficient process
of transfer to high wavenumber, increases the fluctuation level by more than an order
of magnitude. Saturation by damped modes explains why the turbulence and transport
rates of gyrokinetic models for ITG turbulence are insensitive to the number of modes
resolved in scales where the growth rate is not positive. Because the strongest damped
mode in ITG turbulence is a tearing parity mode [5], it also explains why the magnetic
field becomes stochastic, even at very low values of beta (∼0.1 %) [6].

Analysis of ITG turbulence reduction by zonal flows has not accounted for damped
modes. Likewise, the reduction of turbulence saturation levels by damped modes has not
accounted for zonal flows. Clearly there is a need to analyze both of these effects jointly.

2 Zonal Flow/Damped Mode Interactions in a Fluid Model

We examine a fluid model for ITG turbulence that was developed specifically to examine
the effects of zonal flows [7]. The model couples equations for ion pressure and vorticity,

$$\frac{\partial p_k}{\partial t} + i k_y (1 + \eta) \phi_k + \chi k^4 p_k = - \sum_{k'} (k' \times \hat{z} \cdot k) \phi_{k'} p_{k-k'},$$  \(1\)

$$[\delta(k_y) + k^2] \frac{\partial \phi_k}{\partial t} + i k_y \phi_k - ik_y \epsilon p_k + \nu k^2 \phi_k = - \frac{1}{2} \sum_{k'} (k' \times \hat{z} \cdot k) [(k - k')^2 - k^2] \phi_{k'} \phi_{k-k'},$$  \(2\)

where \(\nu\) and \(\chi\) are coefficients of collisional dissipation, \(\eta\) is the ratio of density to temper-

ature gradient scale lengths, and \(\epsilon\) is the ratio of density gradient scale length to magnetic
field scale length. The function \(\delta(k)\) enables the strong zonal flow excitation of ITG tur-
bulence. For \(k_y \neq 0, \delta(k) = 1\), while for \(k_y = 0, \delta(k) = 0\). This allows energy transfer
to the zonal flow \(v_Z(k_x) = ik_x \phi_{k_y=0}\) to be stronger by a factor of \(k_x^{-2}\) than it is for ETG
turbulence where \(\delta(k) = 1\) for \(k_y = 0\). From the linear dispersion relation there are two
linear eigenmodes,

$$\omega_{1,2} \approx \frac{k_y}{2[\delta(k) + k^2]} \pm i k_y \left[ \frac{(1 + \eta) \epsilon}{[\delta(k) + k^2]} \right]^{1/2} - \frac{i \nu k^2}{2[\delta(k) + k^2]} - \frac{i \chi k^4}{2}. $$

The frequency \(\omega_1\) is the ITG mode, and \(\omega_2\) is a damped, nearly conjugate mode. Collisional
dissipation \(\nu\) and \(\chi\), whose rates are assumed to be small compared to the diamagnetic
frequency, breaks the conjugate symmetry. The dynamical equations can be decomposed into equations for the nonlinear evolution of the unstable and stable eigenmode amplitudes $\beta_1$ and $\beta_2$ (which are defined for all wavenumbers such that $k_y \neq 0$), and zonal pressure $p(k_x)$ and flow $v_Z(k_x)$ at $k_y = 0$ [8].

$$\dot{\beta}_1 + i\omega_1 \beta_1 = \sum_{k'} C_{lmn}^r \beta_{m}^{n} |_{k_y \neq 0, k_y} + \sum_{k'_y} \left\{ C_{lFm} v'_Z \beta_{m}^{n} + C_{lFm} p'_Z \beta_{m}^{n} \right\} |_{k'_y = 0},$$

$$+ \left[ C_{lmF} v''_Z \beta_{m}^{n} + C_{lmP} p''_Z \beta_{m}^{n} \right]|_{k'_y = k_y},$$

(3)

$$\dot{v}_Z + \frac{v k^2}{\delta + k^2} v_Z = \sum_{k'_y} \left[ C_{Fmn} \beta_{m}^{n} \right]|_{k'_y = 0},$$

(4)

$$\dot{p}_Z + \frac{\chi k^4}{\delta + k^2} p_Z = \sum_{k'_y} \left[ C_{Pmn} \beta_{m}^{n} \right]|_{k'_y = 0},$$

(5)

Here $l$, $m$, and $n$ assume values of 1 or 2 and repeated indices are summed over. A shorthand notation has been introduced in which $\beta_{1,2} = \beta_{1,2}(k)|_{k_y \neq 0}; \beta_{1,2} = \beta_{1,2}(k)|_{k'_y \neq k_y}$. For the zonal flow $v_Z = ik_x \phi_{k}|_{k_y = 0}$, $v'_Z = ik'_y \phi_{k}|_{k'_y = 0}$, and $v''_Z = i(k_x - k'_y) \phi_{k-k'}|_{k'_y = k_y}$. For the zonal pressure, $p_Z = p(k)|_{k_y = 0}$, $p'_Z = p(k)|_{k'_y = k_y}$, and $p''_Z = p(k-k')|_{k'_y = k_y}$. The coupling coefficients are functions of the nonlinear coefficients of the pressure and vorticity equations, and the components of the eigenvectors, $R_{1,2} = [-\omega_{1,2}(\delta + k^2) + k_y - i k^2]/\delta k_y$. For large wavelengths, $C_{lmn} = (1)^{l-1}(k \times \hat{z} \cdot k)(R^m_{R} - R^m_{-R})/[2(R_1 - R_2)]$, $C_{lFm} = i(1)^{l-1}(k_y R^m_{R} - R^m_{-R})/[2(R_1 - R_2)]$, $C_{lPm} = i(1)^{l-1}(k_y R^m_{R} - R^m_{-R})/[2(R_1 - R_2)]$, and $C_{lFm} = i(1)^{l-1}(k_y k'_y)/[2(R_1 - R_2)]$. Note that the transfer coefficients involving the zonal flow are proportional to $k$, whereas the other coefficients are proportional to $k^2$. Moreover, $C_{Fmn}$, the coefficient that sets the rate of transfer to zonal flows, is larger in the ITG case by a factor of $k^{-2}$ than it is in the ETG case. Consequently, while zonal flows occur for both cases, the zonal flow level is much larger in the ITG case.

The energy is given by $E = \sum_{k}|(\delta + k^2)| \phi_k|^2 + |p_k|^2$. In terms of the eigenmode amplitudes and zonal fields the energy is $E = \sum_{k_y \neq 0}|(1 + k^2 + R_1^2)| \beta_1|^2 + (1 + k^2 + R_2^2)| \beta_2|^2 + 2(1 + k^2) Re(\beta_1^{*} \beta_2) + 2 Re(R_1^* R_2^* R_2 R_1^* R_2^* R_2^* R_2^* R_2^* R_2^* R_2^* R_2^* R_2^* R_2^* R_2^* R_2^* R_2^*) \sum_{k_y = 0}|p_k|^2 + (\delta + k^2)| \phi_k|^2$. Energy is injected into the system by the instability at a rate governed by the growth rate and the amplitude level. For a turbulent steady state it is dissipated at the same rate by the damped mode, which has sinks at the scales of the instability, and by collisional dissipation, which operates in both the unstable and damped modes at small scale. We track this energy from the energy evolution equation, obtained by taking the time derivative of the equation for $E$. From the above expression, that has terms proportional to $d|\beta_1|^2/dt, d|\beta_2|^2/dt, dRe(\beta_1^{*} \beta_2)/dt, dRe(R_1^* R_2^* R_2 R_1^* R_2^* R_2^* R_2^* R_2^* R_2^* R_2^* R_2^* R_2^* R_2^* R_2^* R_2^* R_2^* R_2^* R_2^* R_2^* R_2^* R_2^* R_2^* R_2^* R_2^* R_2^* R_2^* R_2^* R_2^* R_2^*)$ \sum_{k_y = 0}|p_k|^2 + (\delta + k^2)| \phi_k|^2$. Considering the $k$ dependence of these terms we can write $dE/dt = Q_u + Q_1 + Q_n + D + D_Z$. Here, $Q_u = \sum_{k_y < k_{y_{m}(n)}}(1 + k^2 + |R_1|^2) \gamma_1 |\beta_1|^2$ is the energy injected by the instability,
where \( k_y^{(un)} \) is the wavenumber below which \( \gamma_1 > 0 \) and above which \( \gamma_1 < 0 \). Similarly, \( Q_s = \sum_{k_y < k_y^{(un)}} (1 + k^2 + |R_2|^2) \gamma_1 |\beta_2|^2 \) is the energy removed by stable modes in the wavenumber range of the instability. The sum of these terms for \( k_y > k_y^{(un)} \) defines \( D = \sum_{k_y > k_y^{(un)}} (1 + k^2 + |R_1|^2) \gamma_1 |\beta_1|^2 + \sum_{k_y > k_y^{(un)}} (1 + k^2 + |R_2|^2) \gamma_1 |\beta_2|^2 \). The remaining terms in the energy evolution equation are \( Q_{us} \) and \( D_Z \). The former is the rate of change of energy due to the cross terms \( Re(\langle \beta_1 \beta_2^* \rangle) \) and \( Re(\langle R_1^* \beta_1^* R_2 \beta_2 \rangle) \). The latter is the energy damping rate of the zonal fields due to weak collisional dissipation.

We now consider the saturated state for both the ETG case where \( \delta = 1 \) for all \( k_y \) and the ITG case where \( \delta|_{(k_y=0)} = 0 \). From numerical solutions, the energy \( E \) is larger in the ETG case by approximately \( 10^2 \), i.e., \( E_{ETG}/E_{ITG} \approx 10^2 \). This is the well-known effect that the significantly larger zonal flows for the ITG case lead to a lower turbulence level. When \( |D| \) is at its largest the dissipation rates approximately follow the ratios \( Q_u : Q_s : D = 8 : (-7) : (-1) \) in both cases, with \( Q_{us} \) and \( D_Z \) making negligible contributions. This indicates that in both cases most of the energy is damped by the damped mode in the wavenumber range of the instability. The small fraction damped by \( D \) represents the damping by the saturation mechanism associated with energy transfer to high \( k \), which prior to the discovery of the effect of damped modes had been assumed to be the dominant saturation mechanism. The system has been initiated as an ETG case and integrated to a saturated state. At some point \( \delta|_{(k_y=0)} = 0 \) is imposed, converting the system to ITG turbulence with its larger zonal flow level. As the zonal flows build up, \( E \) decreases by \( 10^{-2} \). The rates \( Q_u, Q_s, \) and \( D \) also decrease, each by essentially the same factor of more than an order of magnitude. The decrease in energy rates occurs in parallel with the amplitude reduction. The ratio \( Q_u : Q_s : D \) remains roughly \( 8 : (-7) : (-1) \). This indicates that damped modes dissipate most of the instability energy in both cases, but that energy transfer to the damped mode is more efficient in the ITG case, allowing lower levels. The ratio \( Q_s : D \) does not decrease, indicating that there is no enhanced dissipation at high \( k \) due to enhanced energy transfer to those wavenumbers. What accounts for the differences between the ITG and ETG cases? To answer this question consider the energetics of the unstable mode, focusing on the ITG case.

Energy enters the system through the instability at a rate given by \( \sum (1 + k^2 + |R_1|^2) \gamma_1 |\beta_1|^2 \). We examine the equation for \( d|\beta_1|^2/dt \) to see where that energy goes. The equation is given by

\[
\frac{\partial}{\partial t} \sum_{k_y \neq 0} \left[(1 + k^2 + |R_1|^2)|\beta_1|^2\right] = \sum_{k_y \neq 0} 2(1 + k^2 + |R_1|^2) \gamma_1|\beta_1|^2 + \sum_{k_y \neq 0} N_{111} + N_{112} + N_{121} + N_{122} + N_{11P1} + N_{11P2} + N_{11R} + N_{12P} + N_{1F1} + N_{1F2} + N_{1F1} + N_{1F2},
\]

where the terms labeled by \( N \) represent three-wave coupling terms. The term \( N_{111} \) contains \( \langle \beta_1^* \beta_1^* \beta_1^* \rangle \) describing the correlation between three unstable modes at wavenumbers \( k, k', \) and \( k-k' \). The terms \( N_{112} \) and \( N_{121} \) contain \( \langle \beta_1^* \beta_1^* \beta_2^* \rangle \) and \( \langle \beta_1^* \beta_2^* \beta_2^* \rangle \), describing the correlation between two unstable modes and one stable mode. The term \( N_{122} \) contains \( \langle \beta_1^* \beta_2^* \beta_2^* \rangle \), correlating an unstable mode with two stable modes. None of these involve a zonal flow or zonal pressure. The remaining terms, \( N_{1P1}, N_{1P2}, N_{11P}, N_{12P}, N_{1F1}, N_{1F2}, \)
$N_{11F}$, and $N_{12F}$, do involve a zonal flow or pressure. These eight terms describe energy transfer in triplets with one unstable mode, a zonal field (either pressure or flow) and a third mode that is either stable or unstable. The simulations show that the first term on the RHS of Eq. (6), the energy input rate, is large and positive, that the terms $N_{111}$, $N_{112}$, $N_{121}$, and $N_{122}$ are mostly negative and of the order of 25% of the energy input rate, in aggregate. The remaining eight terms with a zonal field in the triplet are large and negative, and of the order of 75% of the energy input rate.

We investigate further, measuring $N_{1P1} + N_{I1P}$, $N_{12P} + N_{1F2}$, $N_{1F1} + N_{11F}$, and $N_{1F2} + N_{12F}$ separately. The results are shown in Fig. 1. Two sets of nonlinear terms are negligible; the other two sets dominate. The first is the coupling between the unstable mode at $k$, a zonal flow, and a second unstable mode ($N_{1F1} + N_{11F}$). This term is positive, which means that energy is flowing into unstable modes from this term. Since this energy transfer is summed over all nonzonal wavenumbers, the net transfer of energy between the unstable mode at $k$ and the unstable mode at $k'$ or $k''$ should cancel. Consequently, the energy transfer $N_{11F} + N_{1F1}$ is coming entirely from the zonal flow. The terms $N_{1F2} + N_{12F}$ represent energy flowing out of the unstable mode to either the zonal flow or the damped mode. If we take values at $t = 400$ for comparison purposes, 3100 units of energy flow out of the unstable mode per unit time and into the zonal flow and damped mode. Since 1900 units of time flow back into the unstable mode from the zonal flow through $N_{11F} + N_{1F1}$, 1200 units of energy flow to the stable mode per unit time. The 1900 units represent energy that recirculates within the unstable mode. Note from Fig. 1 that very little energy transfer is associated with correlations that involve the zonal pressure.

In this analysis we make use of the fact that very little energy is dissipated by the zonal flow. That piece of information is obtained by deriving the equation for $d[\sum k^2 |\phi|^2]/dt$. The equation has terms representing the energy lost per unit time from collisional dissipa-

\[ FIG. 1: \text{Energy rate terms in Eq. (6) that involve a zonal field in the triplet correlation.} \]
tion and energy transfer to the zonal flow. The latter occurs through triplet correlations with two unstable modes, two damped modes, or an unstable and a damped mode. Energy transfer to the zonal flow has a high degree of variability, with all of the energy transfer terms both depositing energy into the zonal flow and removing it at different instances of time. Averaging over time, the terms proportional to \( \langle v_Z \beta_1' \beta_2'' \rangle \big|_{k_y=0} \) and \( \langle v_Z \beta_2' \beta_1'' \rangle \big|_{k_y=0} \) deposit net energy into the zonal flow. In the units of Fig. 1, this energy is about 2/unit time. The term proportional to \( \langle v_Z \beta_1' \beta_2' \rangle \big|_{k_y=0} + \langle v_Z \beta_2' \beta_1' \rangle \big|_{k_y=0} \) is close to zero on average.

The two units of net energy deposited into the zonal flow is balanced by the collisional dissipation. This indicates that of the energy exchanged between the unstable mode, the stable modes, and the zonal flow, all but a tiny fraction (<1%) goes from unstable mode to stable mode. The energy that goes to the zonal flow is dissipated by the small amount of collisions, indicating that the zonal flow saturates by weak collisional dissipation. It is evident that the zonal flow acts as a catalyst for energy transfer from unstable to stable mode.

To understand why the interaction of the unstable mode, the zonal flow, and the stable mode produces a much more efficient energy transfer channel than the other channels measured, we consider the nonlinear transfer rate that dominates Fig. 1. For small wavenumber \( k^2 \ll 1 \), \( N_{12F} \) is given by

\[
N_{12F} = \sum_{k_y \neq 0} \left( 1 + |R_1|^2 \right) Re \left( \frac{-i}{R_1 - R_2} \sum_{k_y} k_y R_2' \langle \beta_1' v_Z' \beta_2'' \rangle \right),
\]

where \( N_{1F2} \) has the same form with \( '' \) and \( ' \) interchanged. As already noted, transfer rates involving the zonal flow are large because the coupling coefficients are large (for the ITG case). The coupling coefficients in Eq. (7) are the factors multiplying the triplet correlation \( \langle \beta_1' v_Z' \beta_2'' \rangle \). Transfer involving zonal flows is also large because \( v_Z \) becomes large when the coupling is enhanced. These effects explain why both the terms \( N_{11F} + N_{1F1} \) and \( N_{1F2} + N_{12F} \) are large in Fig. 1. A remaining effect is responsible for enhancing \( \langle \beta_1' v_Z' \beta_2'' \rangle \), but not correlations of \( N_{11F} + N_{1F1} \). If we write down the nonlinear evolution equation for \( \langle \beta_1' v_Z' \beta_2'' \rangle \) and invert it, it has the form,

\[
\langle \beta_1^* v_Z'' \beta_2'^* \rangle = \frac{\hat{G}}{i[\hat{\omega}'_F + \hat{\omega}'_2 - \hat{\omega}_1^*]},
\]

where \( \hat{G} \) is proportional to quartic correlations, and \( \hat{\omega}'_F \), \( \hat{\omega}'_2 \), and \( \hat{\omega}_1^* \) are the complex frequencies of the zonal flow, damped mode, and unstable mode at finite amplitude. These finite-amplitude frequencies were evaluated from the simulations. The factor \( [\hat{\omega}'_F + \hat{\omega}'_2 - \hat{\omega}_1^*]^{-1} \) is a nonlinear interaction time for the triplet correlation \( \langle \beta_1^* v_Z'' \beta_2'^* \rangle \) responsible for energy transfer from the unstable mode to the damped mode. This time is maximum when \( \hat{\omega}_F + \hat{\omega}_2 - \hat{\omega}_1^* \) is minimum. Analysis of this frequency sum shows that it is as much as an order of magnitude smaller than frequency sums that do not involve the combination of an unstable mode, the zonal flow, and the stable mode.
3 The Tearing Parity Damped Mode and Electron Thermal Transport

In gyrokinetic simulation of ITG turbulence there is not a single excited damped mode, but many damped modes are excited. Proper orthogonal decomposition (POD) of electromagnetic CYCLONE base case ITG turbulence using GENE reveals that the most important damped mode excited, in terms of its contribution to fluctuation energy, is a tearing-parity mode. This causes the magnetic field to become stochastic at low $\beta$ values (e.g., $\beta_e = 0.1\%$). The dominant POD mode ($n = 1$) is the unstable ITG mode, which for $k_x = 0$, has even ballooning parity along the field, and is therefore unable to reconnect magnetic field lines. The $n = 2$ mode has tearing parity. Even for $k_x \neq 0$, the first two POD modes are dominantly a ballooning and a tearing parity mode. When the electromagnetic heat flux spectrum is decomposed into POD modes, these account for very nearly all of the flux. The ballooning component produces a negative dip at the $k_y$ value where the ion heat flux peaks, and the tearing component produces positive values at lower and higher $k_y$. The tearing component scales like $\beta_e^2$, and dominates the flux as $\beta_e$ increases. Figure 2 shows the energy in the tearing component (black) and

![Image of energy transfer rate](image)

**FIG. 2:** Energy transfer rate to the tearing parity mode. The high degree of correlation between the full nonlinear rate (red) and the nonlinear rate for triplets involving the zonal flow (blue) indicates that most energy going to the tearing mode involves a triplet with the zonal flow.

the nonlinear drive (red), which is the time derivative of energy. The component of the drive that couples with zonal wavenumber ($k_y = 0$) is shown in blue. Its near match with the red trace indicates that most of the nonlinear drive of the tearing component is associated with an interaction with zonal wavenumbers, consistent with the description of the previous section. Zonal wavenumbers are thus associated with an *increase* in electron heat transport through the tearing-parity damped mode.
4 Damped-Mode Ion Heat Flux Reduction

Damped modes reduce the ion heat flux in ITG turbulence. A magnetic shear scan provides details of the complicated nature of this effect. At high values of shear, damped modes nonlinearly modify the response of the dominant mode in a singular value decomposition, reducing the flux from its quasilinear value by a factor 1.4. At low shear there are multiple unstable modes, which raise the heat flux. An observed decrease by a factor of 2.8 indicates that damped modes more than offset the effect of multiple unstable modes. Observations in Tore Supra show ratios of $Q_{q*}/Q$ greater than unity, with an increase in this ratio when the magnetic shear is weaker [9]. An increase in zonal flow levels is also observed. Since zonal flows do not directly modify the heat flux, damped modes are a compelling candidate for the Tor Supra observations.

5 Conclusions

The well known role of zonal flows in reducing ITG turbulence has been shown to occur because zonal flows create a highly efficient transfer of energy to damped modes, which remove energy at the large scales of the instability. This process is different from E×B shearing. In gyrokinetic simulations at finite beta, the most energetic of many damped modes is a microtearing mode. It makes the magnetic field stochastic, and causes electron thermal transport. Because the zonal flow catalyzes efficient transfer to this mode, the zonal flow reduces ion heat transport, but enhances electron heat transport.

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References