On the dynamics of large-scale structures in electron temperature gradient turbulence

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Abstract

The electron temperature gradient mode has been proposed to be a source of experimentally relevant electron thermal transport, via a variety of nonlinear phenomena such as the generation of streamers. The question of streamer stability and saturation is revisited, with the effects of geometry and perturbation stability highlighted. It is shown that the streamer saturation level is *not* determined by the balance of Kelvin-Helmholtz rate vs. linear growth rate, but by balancing the nonlinear Kelvin-Helmholtz drive against *damping* mechanisms of the Kelvin-Helmholtz perturbation. In addition, random shear suppression of ETG turbulence by drift-ion temperature gradient (DITG) modes is studied, and it is found that streamers will be sensitive to shearing by short-wavelength DITG modes. An additonal interaction mechanism, modulations of the electron temperature gradient induced by the DITG turbulence, is considered and shown to be quite significant. These considerations are used to motivate a discussion of the requirements for a credible theory of streamer transport.

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1 Introduction

One of the central, outstanding questions in magnetic confinement based fusion energy research is understanding the source of anomalous electron transport [1], particularly in the case of internal transport barriers in which particle

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and ion thermal transport have been suppressed [2–4]. Recently, the electron temperature gradient (ETG) mode [5–8] has become a popular explanation for anomalous electron thermal transport, for several reasons. First, it has a very small characteristic scale ρ_e ($\rho_e = v_{Te}/\Omega_{ce}$, $v_{Te} = \sqrt{T_e/m_e}$, $\Omega_{ce} = |e|B/m_e c$) and fast time scale $\sqrt{L_{Te}L_B}/v_{Te}$ (for curvature-driven ETG, which is expected to be the most important from a transport standpoint), which indicate it should be insensitive to the large-scale equilibrium shear flows which are believed to lead to the suppression of particle and ion thermal transport (via suppression of the ion temperature gradient (ITG) [9] and trapped electron (TEM) [10–14] modes, which have larger characteristic spatial scales ρ_i and slower timescales $\sqrt{L_{Ti}L_B}/v_{Ti}$). Secondly, the ETG mode is presumed to exist in the region where $k_\perp \rho_i >> 1$, which leads to an essentially adiabatic ion density response, implying that it will drive negligible particle or ion thermal transport. Finally, a number of machines have reported evidence for a "critical gradient" for electron transport [15–18], which is expected from the form of the linear growth rate for the ETG mode. The major difficulty in invoking ETG turbulence is that its characteristic spatial and temporal scales give a mixing length thermal diffusivity $\chi_e^{ETG} \sim \rho_e^2 v_{Te}/L_{Te}$ which is much to small to explain the observed transport. However, certain recent simulations have suggested that ETG turbulence can exhibit streamer formation [19–22] i.e. the formation of large scale, radially extended structures which might greatly increase the radial correlation length, and thereby increase the transport above the basic mixing length estimate. In addition, there are also arguments that inverse cascade dynamics in the magnetic fluctuations of the could make the correlation length of the turbulence on the order of the electron skin depth $\delta = c/\omega_{pe} >> \rho_e$ [1,23], again raising the effective diffusivity to experimentally relevant levels. Indeed, the enthusiasm for the ETG mode has reached such a level that it is sometimes invoked to explain not just electron thermal transport in cases where ITG and TEM modes are believed suppressed, but in the bulk of the plasma (e.g. in regions without internal transport barriers, and "*L*-mode" plasmas) [16,17], effectively overwhelming the electron thermal transport due to ITG and TEM modes. Given the importance of electron transport in understanding current machine performance, and predicting future performance, it is clearly important to have a thorough analytical understanding of the mechanisms which drive the transport. In particular, understanding streamer dynamics represents an important and intriguing topic for the fusion theory community, because of their potential impact and implications for electron thermal transport, and their inherent basic science motivation in the context of pattern formation in a nonlinear system.

Another challenge frequently encountered in problems of self-organization and structure / pattern formation is concerned with quantitatively understanding the interaction between bands of turbulence with disparate scales. These types of problems are central to the process of zonal flow formation in planetary atmospheres and confined plasmas, and dynamo generation of magnetic fields, but have not been deeply explored in the context of transport predictions. In most theories and models of turbulent transport, there is assumed to be one dominant type of instability (such as ion temperature gradient-driven drift-waves (DITG) or resistive interchange modes [24]) which is taken as the sole driver of all of the transport channels. In reality, however, multiple instabilities on different scales may coexist (i.e. DITG on $\rho_s = c_s/\Omega_{ci}$ scales, and ETG modes on ρ_e scales). Previously, it has been argued (or more often, tacitly assumed) that the separation in temporal and spatial scales meant that interactions between instabilities on different scales were generally negligible relative to the nonlinear "self" interactions of a particular instability. For instance, the effects of ETG turbulence on DITG turbulence and vice versa (such as the shearing of ETG eddies by the DITG flow field, or the Reynolds stress of the ETG turbulence on the DITG turbulence) were ignored. In particular, with the *possible* highly specialized exception of electron thermal transport in barrier regiemes where drift-ITG turbulence has been supressed, ETG fluctuations must *always* be considered in the context of the drift-ITG background. This questions becomes particularly relevant for the case of streamer driven transport (or electron skin-depth scale eddies), where the transport-relevant scales are much greater than ρ_e, thus reducing the effective separation between the ETG-driven transport and DITG scales, and thereby increasing the likelihood of significant shearing interactions between the transport-driving structures and the DITG turbulence. More generally, the problem of how different different scales of turbulence interact is also of intrinsic interest as a novel problem in nonlinear dynamics. The generic structure of this problem has been considered by Itoh *et al.* [25,26].

The remainder of the paper is structured as follows: In Sec. 2, we discuss the stability of streamers to nonlinear Kelvin-Helmholtz breakup in the context of the Hasegawa-Mima system [27], and mechanisms for their saturation. In Sec. 3, interactions between ETG and DITG modes are considered, due to both the shearing of ETG turbulence by the DITG flow, and by DITG-induced modulations of the electron temperature profile. Motivated by these considerations, we present some nessecary critera for developing a credible theory of physicaly relevant streamer-driven transport in Sec. 4. Conclusions and future directions are presented in Sec. 5.

2 Streamer physics

In both ETG and ITG turbulence simulations, radially extended convective cells termed streamers have been observed, with correlated increases in the turbulent heat flux. Such structures are particularly important for ETG turbulence, as they potentially offer a mechanism for raising the turbulent transport to experimentally relevant values. To understand the impact of streamers on transport, several questions must be answered, such as:

(1) For what parameters do streamers exist? (Generation *and* stability)
(2) What determines the intensity of the streamers? (Saturation mechanism)
(3) What determines the poloidal and radial scales of the streamers?

In this section, we offer some insights into these questions, via considerations from a simple analytic model.

2.1 Streamer Classification

The first step in any theory of streamers is to mathematically define what a streamer is. This issue is non-trivial, as streamers remain somewhat ambiguous concept in the fusion community. Towards this end, one might note that various "observations" of streamers could be put into two different groups: the streamer as an isolated burst (in a background of smaller-scale, (quasi-) isotropic turbulence), such as shown in Refs. [19] and [28], and the streamer array (an array of poloidally "stacked," radially extended convective cells), such as that shown in Refs. [20,22,29,30]. The isolated burst streamer is often observed intermittently, whereas the steamer array is generally a fairly static structure. Also note that while the isolated burst case is clearly related to highly nonlinear dynamics of the turbulence, the second case could arrive from linear *or* nonlinear processes.

Analytic treatment of the "isolated burst" streamer is in general quite difficult, because of the difficulty in mathematically defining the streamer structure, and because of its intermittent nature. Such structures naturally motivate probabilistic approaches i.e. determining the probability of a structure of a certain size to be formed, and its impact on the probability distribution function (PDF) of various fluxes. Initial progress towards using this approach has been reported by Kim and Diamond [31], who used a path-integral approach to calculate the tails of the momentum flux PDF in the Hasegawa-Mima framework. In a related vein, Nevins has reported on the use of "heat pulse analysis" in determining the scaling of heat flux with system size [32,33]. In this analysis, the (flux-surface averaged) heat flux is decomposed into events of different scales, and the PDF of events as a function of scale is investigated. Approaches such as these are clearly quite promising in aiding understanding of the highly nonlinear dynamics of the turbulence, and should receive more attention. In contrast to the "isolated burst" case, the streamer array is more readily tractable to direct analytic analysis, and it is this case upon which we focus for the remainder of this paper.

One of the first questions one might ask about a streamer array is whether such a system is stable. Indeed, basic intuition from fluid dynamics suggests that such a structure could be unstable to a Kelvin-Helmholtz (K-H) type breakup [34]. In magnetized plasmas, the basic aspects of stability can be found by considering the stability of the structure in the context of the Hasegawa-Mima system [27], which is the prototypical equation for drift-wave turbulence. The Hasegawa-Mima equation has the form:

$$\left(1-\nabla_\perp^2\right)\frac{\partial\phi}{\partial t}+\frac{\partial\phi}{\partial y}=\{\phi,\nabla_\perp^2\phi\} \tag{1}$$

Here, the normalizations are $x, y \to x, y/\rho$, $\rho = V/\Omega_c$, $\Omega_c = |q|B/mc$, $V = \sqrt{T_e/m}$, $t \to Vt/L_n$, $L_n = -d\ln n_o/dx$, and ϕ to the mixing length level $\phi = (L_n/\rho_s)\,|e|\tilde{\phi}/T_e$. The Poisson brackets $\{\phi,\nabla_\perp^2\phi\} = \partial_x\phi\partial_y\left(\nabla_\perp^2\phi\right) - \partial_y\phi\partial_x\left(\nabla_\perp^2\phi\right)$ represent the convection of vorticity $\nabla_\perp^2\phi$ by the $\vec{E}\times\vec{B}$ velocity $\vec{v}_{ExB} = \left(c/B^2\right)\vec{E}\times\vec{B} = -\vec{\nabla}\phi\times\hat{z}$.

We assume there exists a initial streamer array ϕ_s of the form

$$\phi_s = \phi_q e^{i(qy-\Omega_q t)} + c.c. \tag{2}$$

$$\Omega_q = \frac{q}{1+q^2} \tag{3}$$

Note that the streamer has a real frequency Ω_q, which is neglected in earlier treatments of the instability [19,21]. Noting that the streamer is periodic in $\psi_q = qy - \Omega_q t$, Floquet theory is used to write the perturbation in the form

$$\delta\phi = \sum_{n=-\infty}^{\infty}\phi_n e^{ipx+in\psi_q} + c.c. \tag{4}$$

For tractability, we restrict the range of n from -1 to 1, which is equivalent to considering the stability of the streamer in the context of a four-wave coupling problem (i.e. a K-H perturbation ϕ_0 and two sidebands $\phi_{\pm1}$); it can be shown that the requirements on matching wavenumbers and frequencies makes the three-wave case inefficient. One can then directly derive the evolution equations for the perturbation modes

$$\frac{\partial\phi_0}{\partial t} = -\frac{qp^3}{1+p^2}\left(\phi_q\phi_{-1} - \phi_q^*\phi_1\right) \tag{5}$$

$$\frac{\partial \phi_1}{\partial t} - i\Delta\Omega\phi_1 = \frac{qp\left(q^2-p^2\right)}{1+q^2+p^2}\phi_q\phi_0 \tag{6}$$

$$\frac{\partial \phi_{-1}}{\partial t} + i\Delta\Omega\phi_{-1} = -\frac{qp\left(q^2-p^2\right)}{1+q^2+p^2}\phi_q^*\phi_0 \tag{7}$$

$$\Delta\Omega = \Omega_q - \frac{q}{1+q^2+p^2} = \frac{qp^2}{\left(1+q^2\right)\left(1+q^2+p^2\right)} \tag{8}$$

The growth rate is found to be

$$\gamma_{KH}^2 = 2\frac{q^2p^4\left(q^2-p^2\right)}{\left(1+q^2\right)\left(1+q^2+p^2\right)}|\phi_q|^2 - \Delta\Omega^2 \tag{9}$$

In the limit of $q, p << 1$, which is relevant for streamers which might have a meaningful impact on transport, one finds

$$\gamma_{KH}^2 \simeq 2q^2p^4\left(q^2-p^2\right)|\phi_q|^2 - \left(qp^2\right)^2 \tag{10}$$

The first term in Eqn. 10 is what one might call the "usual" K-H growth rate, which indicates that the perturbation wavenumber p must be smaller than the streamer wavenumber q for instability, reflecting the "inverse cascade" property of the nonlinearity (i.e. the streamer transfers energy to larger scale modes), in agreement with previous studies. The second term, which has not been previously reported, represents the stabilizing influence of the frequency mismatch between the base frequencies of the streamer and the sidebands. The effect of this term is to indicate that there is a *minimum intensity for streamer breakup*. It is easy to see that this condition is given by

$$\phi_q > \frac{1}{\sqrt{2\left(q^2-p^2\right)}} \tag{11}$$

Equivalently, one might also say that for a given streamer intensity, the perturbation wavelength p must be less than a critical wavenumber k_c,

$$k_c = q\sqrt{1-\frac{\phi_c^2}{\phi_q^2}} \tag{12}$$

$$\phi_c = \frac{1}{\sqrt{2}q} \tag{13}$$

One can also maximize Eqn. 10 over the K-H wavelength p, to find

$$p_{max} = \sqrt{\frac{2}{3}}k_c \tag{14}$$

$$\rightarrow \gamma_{KH}^{max} = \gamma_0 \frac{\phi_q}{\phi_c}\left(1 - \frac{\phi_c^2}{\phi_q^2}\right)^{3/2} \tag{15}$$

$$\gamma_0 = \left(\frac{2}{3}\right)^{3/2} \phi_c = \frac{2}{3\sqrt{3}} q^3 \tag{16}$$

This result (Eqn. 15) is plotted in Fig. 1.

2.3 Effects of Linear Growth and Damping Rates

While one can gain some basic insights into streamer stability through the approach taken in the previous section, one would like to undertake a more rigorous analysis of the problem. In particular, self-consistently including the fact that the full ETG system is described by coupled electrostatic potential, pressure, and magnetic fluctuation fields, with linear growth and damping rates, would be desirable. While such an approach is technically possible, interpretation of the results rapidly becomes quite difficult; work along these lines will be reported upon in a future publication.

A more tractable problem is to add a set of ad-hoc damping rates to the one-field set of equations derived above. Defining the damping rate of the K-H perturbation as ν_{KH} (note that the K-H mode is a purely radial mode which cannot extract energy from the background profile, and so must be damped), and the damping rate of the sidebands as γ_{SB}, one can write an updated set of equations for the perturbation evolution as

$$\frac{\partial \phi_0}{\partial t} = -\nu_{KH}\phi_0 - qp^3\left(\phi_q\phi_{-1} - \phi_q^*\phi_1\right) \tag{17}$$

$$\frac{\partial \phi_1}{\partial t} = -\left(\gamma_{SB} - i\Delta\Omega\right)\phi_1 + qp\left(q^2 - p^2\right)\phi_q\phi_0 \tag{18}$$

$$\frac{\partial \phi_{-1}}{\partial t} = -\left(\gamma_{SB} + i\Delta\Omega\right)\phi_{-1} - qp\left(q^2 - p^2\right)\phi_q^*\phi_0 \tag{19}$$

$$\Delta\Omega = qp^2$$

Here, we have again assumed q, $p << 1$ for simplicity. The dispersion relation with the inclusion of the damping rates can be derived as

$$\left(\gamma + \nu_{KH}\right)\left(\left(\gamma + \gamma_{SB}\right)^2 + \Delta\Omega^2\right) = \gamma_{KH}^2\left(\gamma + \gamma_{SB}\right) \tag{20}$$

$$\gamma_{KH}^2 = 2q^2p^4\left(q^2 - p^2\right)|\phi_q|^2 \tag{21}$$

In the limit that $|\Delta\Omega/\left(\gamma + \gamma_{sb}\right)| << 1$, which should be true for the assumption that q, $p << 1$, the net growth rate can then be solved as

$$\gamma \simeq -\frac{\gamma_{SB} + \nu_{KH}}{2} + \sqrt{\gamma_{KH}^2 - \Delta\Omega^2 + \frac{1}{4}\left(\nu_{KH} - \gamma_{SB}\right)^2} \tag{22}$$

The condition on streamer intensity for instability is now

$$\gamma_{KH}^2 > \Delta\Omega^2 + \gamma_{SB}\nu_{KH} \tag{23}$$

$$\rightarrow |\phi_q|^2 > \frac{1}{2\left(q^2 - p^2\right)}\left(1 + \frac{\gamma_{SB}\nu_{KH}}{q^2 p^4}\right) \tag{24}$$

As before, there is a minimum intensity for break-up which depends upon $\Delta\Omega, \gamma_{SB}, \nu_{KH}$. It should be noted that the above set of equations, and resulting physics, is quite similar to the model proposed by Chen et. al. [35] for describing zonal flow generation via the coherent modulational instability of a linearly unstable drift-wave in toroidal geometry. Here, the pump drift-wave of Chen et. al. becomes the streamer, and the zonal flow becomes the K-H perturbation. The key difference is that we have considered the problem in the much simpler Hasegawa-Mima system which omits geometry effects and parallel dynamics, which are well-known to be very important for correctly describing zonal flow dynamics in ITG turbulence (via mechanisms such as magnetic shear stabilization [36,37]). Including the parallel dynamics has significant implications for the overall dynamics here as well. Their significance arises here from the fact that K-H modes with finite $k_{||}$ (essentially acoustic modes) will be strongly damped due to Landau damping, while $k_{||} = 0$ modes (ETG zonal flows) have a much weaker damping rate proportional to a combination of ν_{ei} and ν_{ee} (analogous to the collisional damping of ITG zonal flows) [38]. It should also be remembered that the ion response in ETG is essentially adiabatic for all $k_{||}$, which has the effect of strongly reducing ETG zonal flow growth, relative to the ITG case. In addition, inclusion of the geometry and parallel dynamics will also strongly impact the stability of the sidebands (i.e. γ_{SB}), which is clearly another important factor in determining the minimum streamer amplitude for break-up.

2.4 Streamer Saturation

Complementary to the question of streamer stability and breakup is the question of streamer saturation level, which is crucial to determining the transport resulting from the streamers. Previous attempts have done this by taking the simplistic approach of balancing the linear growth rate against the breakup rate, estimated as the growth rate of K-H mode [19,21]. For $q \simeq p << 1$, and assuming $\phi_q/\phi_c >> 1$, $\gamma_{KH} \propto q^4|\phi_q|$, which gives that $|\phi_q| \sim \gamma_q^{lin}/q^4$. For toroidal ETG modes, $\gamma_q^{lin} \propto q$, giving $|\phi_q| \sim 1/q^3$, which is quite large for $q << 1$. It is then argued that this high saturation level (perhaps combined with the large radial scale of the streamers) leads to experimentally relevant transport levels. However, one need only dig a little deeper to find a significant flaw in this argument: if one notes that the turbulent transport should scale as the intensity of the streamer, i.e. $\chi_{turb} \propto |\phi_q|^2 \sim 1/q^6$, one finds that for realistic values of q ($\sim 0.1\rho_e^{-1}$, based on the previously reported results [19]), one finds a transport level that is in fact unphysically large (e.g. on the order of $10^6\chi_{gyroBohm}$ for the example above).

The resolution to this inconsistency is to note that one should balance the pure K-H drive against the growth and damping rates of the K-H mode and sidebands, rather than the the linear growth rate of the streamer. Eqn. 23 clearly demonstrates this, as marginal stability to K-H perturbation is equivalent to streamer saturation. More directly, one could write a heuristic evolution equation for the K-H mode as

$$\frac{\partial \phi_{KH}}{\partial t} = \gamma_{KH}(q, \phi_q)\,\phi_{KH} - \nu\phi_{KH} \tag{25}$$

where γ_{KH} was calculated above in Eqn. 10, and ν is the rate energy leaves the K-H mode, due to other nonlinear interactions (e.g. a turbulent viscosity), and linear damping effects. Clearly, steady-state / saturation is reached when $\gamma_{KH} = \nu$. One can draw an analogy with the 0-D predator-prey models proposed by Diamond et. al. [39] for drift-wave - zonal-flow interactions, where Eqn. 25 would be combined with a streamer evolution equation of the form

$$\frac{\partial \phi_q}{\partial t} = \gamma_q^{lin}\phi_q - \gamma_{NL}(p, \phi_{KH})\,\phi_q \tag{26}$$

Here, γ_{NL} is the rate energy leaves the streamer mode, *which is in general not equal to* γ_{KH}*!* Here, the appropriate analogy is to momentum transfer rates between electrons and ions. Namely, note that $\nu_{ei} \neq \nu_{ie}$, i.e. the *rate* of momentum transfer to electrons from ions is not the same as the rate of transfer to ions from electrons, but the overall momentum of the system is conserved. Likewise here, the rates of energy transfer are different, but the energy of the system as a whole is (nonlinearly) conserved. In this context, one can calculate the effect of the back-reactions on the streamer, to derive a set of normalized equations which describe the nonlinear evolution of the instability.

$$\frac{\partial A_0}{\partial \tau} = -\Gamma_{KH}A_0 + A_q^*A_+ - A_qA_- \tag{27}$$

$$\frac{\partial A_+}{\partial \tau} = -\left(\Gamma_{SB} - i\beta\right) A_+ + \alpha A_q A_0 \tag{28}$$

$$\frac{\partial A_-}{\partial \tau} = -\left(\Gamma_{SB} + i\beta\right) A_- - \alpha A_q^* A_0 \tag{29}$$

$$\frac{\partial A_q}{\partial \tau} = A_q + A_0 A_-^* - A_0^* A_+ \tag{30}$$

The normalizations used are $\tau = \gamma_q t$, where γ_q is the linear growth rate of the streamer, $\alpha = (q^2/p^2 - 1)$, $\Gamma_{KH} = \nu_{KH}/\gamma_q$, $\Gamma_{SB} = \gamma_{SB}/\gamma_q$, $\beta = \Delta\Omega/\gamma_q = qp^2/\gamma_q$, K-H amplitude $A_0 = q\beta\phi_0$, sideband amplitudes $A_\pm = q\beta\phi_{\pm 1}$, and streamer amplitude $A_q = p\beta\phi_q$. As stated above, this model is quite similar to the one developed by Chen et. al., and might be expected to exhibit similar nonlinear behavior such as a period doubling route to chaos. Such dynamics have interesting implications for intermittency of streamer transport, even for the case of the regular streamer array. Of particular interest is to consider the above model in the limit that $\beta << \Gamma_{SB}$, in which case only the real parts of the equations need be considered. Defining $A_s = A_+ - A_-$, one has

$$\frac{\partial A_0}{\partial \tau} = -\Gamma_{KH} A_0 + A_q A_s \tag{31}$$

$$\frac{\partial A_s}{\partial \tau} = -\Gamma_{SB} A_s + 2\alpha A_q A_0 \tag{32}$$

$$\frac{\partial A_q}{\partial \tau} = A_q - A_0 A_s \tag{33}$$

It is then easy to show that this set of equations has a (non-trivial) fixed point at $A_0 = \sqrt{\Gamma_{SB}/2\alpha}$, $A_s = \sqrt{\Gamma_{KH}}$, and $A_q = \sqrt{\Gamma_{SB}\Gamma_{KH}/2\alpha}$, clearly demonstrating that the streamer saturation level is set by the damping rates of the perturbation. It should also be noted that the existence of the fixed point requires that the sidebands be damped as well as the K-H mode, again highlighting the importance of geometry, parallel dynamics, and other physics not explicitly included in the model used here.

The obvious implication of the above discussion is that the damping rates of the instability (both the primary *and* sidebands) will be crucial for determining the streamer saturation level and thus streamer-driven transport, just as the damping of zonal flows in ITG turbulence is crucial for determining the transport in that system. One might also speculate that the importance of K-H mode damping might explain differences in simulation results. For example, Jenko and co-workers [19,20] and Idomura *et al.* [30] report the existence of strong streamer formation and high transport levels in various gyrokinetic flux-tube and global simulations (respectively), while Labit and Ottaviani report the presence of elongated structures, but no or minimal enhancement of transport [22] in gyrofluid flux-tube simulations with a simplified magnetic geometry, and Lin *et al.* report similar "null" results in a global gyrokinetic simulation [29]. In all cases where streamers were reported to drive significant transport, there was positivie magnetic shear and toroidal curvature effects were strong; conversely, all cases which have considered “slab” geometries with weak curvature effects, or reversed magnetic shear, have exhibited low thermal transport and the formation of ρ_e scale zonal flows; both sets of results highlight the importance of magnetic geometry (and motivate reconsideration of streamer saturation in a more realistic model). We note that in the reverse shear case, the connection between zonal flow stability and low thermal transport has been investigated by Idomura *et al.* [37]. Clearly, this is an issue which requires further study.

3 Interactions between ETG and DITG turbulence

One idea which has recently arisen from studies of ETG turbulence is whether such turbulence would have any effect on the larger scale ITG turbulence it would coexist with [40]. However, with the rise in popularity of the ETG mode as a dominant source of electron heat transport, even in the presence of ITG and TEM turbulence (which we “lump” together as DITG modes, since both have the ion gyroradius as their characteristic scale), it is perhaps more useful to consider the “inverse” question, e.g. how does the presence of DITG modes affect the dynamics of ETG turbulence, particularly large-scale structures such as streamers. Like the question of streamer dynamics, the question of interactions between different scales of turbulence also has an inherent interest as a novel problem of nonlinear dynamics. In this section, we first consider how shearing due to the DITG flow field will affect the ETG turbulence. We then consider the effects of DITG-induced fluctuations of the temperature gradient on the ETG turbulence.

3.1 Shearing of ETG turbulence by DITG modes

We first consider the question of how random shearing by DITG modes might affect ETG turbulence. As described above, the drift-ion temperature gradient (DITG) label applies to both long-wavelength curvature-driven ion temperature gradient instabilities (which have characteristic radial scales of approximately several ρ_s), as well as instabilities with slightly shorter characteristic scales, such as the “universal instability”[41] or the collisionless trapped electron mode [11–14]. We exploit the separation of space and timescales between the DITG and ETG modes to describe the evolution of the ETG turbulence in the presence of the DITG modes by the wave-kinetic equation (WKE) [42]

$$\frac{\partial N}{\partial t}+\frac{\partial}{\partial \vec{k}}\left(\omega_k+\vec{k}\cdot\vec{V}_{DITG}\right)\cdot\frac{\partial N}{\partial \vec{x}}-\frac{\partial}{\partial \vec{x}}\left(\vec{k}\cdot\vec{V}_{DITG}\right)\cdot\frac{\partial N}{\partial \vec{k}}=2\gamma_k N-\Delta\omega N^2 \quad (34)$$

Here, $N=(\tau+k_\perp^2\rho_e^2)^2\left|\phi_k^{ETG}\right|^2+\left|T_k^{ETG}\right|^2$ is the potential enstrophy ($\tau=T_e/T_i$ and $T=\tilde{T}_e/T_{e0}$) , which is the adiabatic invariant [43] associated with the ETG turbulence, while ω_k and γ_k are the linear frequency and growth rate of the ETG modes, respectively, and the $\Delta\omega N^2$ term represents an simplified model for nonlinear self-damping of the ETG turbulence (i.e. turbulent mixing or decorrelation). $\vec{V}_{DITG}=v_{Te}\hat{z}\times\rho_e\vec{\nabla}\phi^{DITG}$ is the flow field of the DITG turbulence (that is, on ρ_s scales and thus large compared to the ρ_e scale ETG turbulence); $\hat{z}=\vec{B}/|B|$ is the unit vector in the direction of the local magnetic field. For both the ETG and DITG modes, $\phi=|e|\tilde{\phi}/T_e$. It is important to note that here $\vec{V}_{DITG}$ represents the flow field of the *entire* DITG turbulence spectrum, not just the flow field associated with the zonal flows driven by that turbulence (as in previous studies which have used the adiabatic theory approach). In particular, we include the fluctuations associated with trapped electron modes and other effects which may be on slightly smaller scales than the fluctuations associated with traditional curvature – driven ITG turbulence (i.e. turbulence with length scales $l\simeq\rho_s$ as well as on scales $l\geq\rho_s$).

The most direct way to estimate the effects of the DITG turbulence is to use a quasi-linear closure of the WKE to derive the k-space diffusion coefficient for ETG modes due to a spectrum of DITG modes $|\phi_q|^2$; this calculation is analogous to that of Diamond *et. al.* [39] in determining the effects of zonal flow shearing on the turbulence which generates the flow. We also note that if there are spatial gradients of the ETG turbulence intensity, the DITG turbulence will induce spatial diffusion. Using this approach, we find

$$\frac{\partial\langle N\rangle}{\partial t}\simeq\frac{\partial}{\partial k_\alpha}D_{\alpha\beta}^K\frac{\partial\langle N\rangle}{\partial k_\beta}+2\gamma_k\langle N\rangle-\Delta\omega\langle N\rangle^2 \quad (35)$$

$$D_{\alpha\beta}^K=\rho_e^2 v_{Te}^2\sum_q q_\alpha q_\beta|\left(\vec{k}\times\vec{q}\right)\cdot\hat{z}|^2 R\left(\Omega_q\right)|\phi_q|^2 \quad (36)$$

$$R\left(\Omega_q\right)=\frac{1}{2\gamma_k-i\left(\Omega_q-\vec{q}\cdot\vec{v}_g\right)}\simeq\frac{1}{2\gamma_k} \quad (37)$$

Here $D_{\alpha\beta}^K$ is a tensor wavenumber-space diffusivity coefficient which represents the generalized random shearing action of the DITG spectrum on the small-scale ETG turbulence spectrum. The angular brackets denote a spatial averaging; thus $\langle N\rangle$ is the ETG intensity averaged over *DITG* (ρ_s) spatial scales. This diffusion tensor represent a direct generalization of previous works (such as Refs. [39,44]) which have used a similar approach to quantify the effects of zonal flow shearing on the underlying turbulence. The tensor structure follows from the fact that the DITG turbulence is a function of both the radius r and polodial angle θ, whereas in the previous approaches the diffusion arose only from the zonal flow spectrum, which is independent of θ. This tensor structure has also been discussed in a different context by Hahm and Burrell [45]. The $R(\Omega_q)$ term (Eqn. 37) represents the response function of the ETG turbulence to mode q of the DITG turbulence; Ω_q is the real frequency of the DITG mode, while $\vec{v}_g$ is the group velocity of the ETG turbulence. The separation of DITG and ETG scales leads to $R(\Omega_q)$ being dominated by the ETG growth rate γ_k.

To estimate the importance of the k-space DITG shearing, one can identify two key timescales: the linear growth rate $\gamma_{lin} = 2\gamma_k$, and the diffusive timescale $\gamma_D \sim D^K_{\alpha\beta}/k_\alpha k_\beta$. One can characterize the strength of the DITG-induced shearing of ETG turbulence by arguing that if $\gamma_{lin} << \gamma_D$ then the k-space diffusion rapidly carries energy to high k where it damps, which effectively means the ETG is strongly suppressed. More colorfully, the DITG shearing field will "rip" the ETG turbulence apart before it can grow to a significant intensity level. In the other limit, the random shearing cannot overcome the linear drive of the ETG, which must then saturate by self-damping. If $\gamma_D \sim \gamma_{lin}$, then one would have a situation in which the DITG shearing was strong enough to significantly lower the saturation level of the ETG turbulence, but would not necessarily completely "quench" it. This regime is particularly relevant for streamers, as in such a case the shearing could reduce the radial correlation length (which serves as a sort of radial step size for the turbulent thermal diffusivity) of the streamers enough to prevent them from driving significant levels of transport, even if they were not entirely suppressed (i.e. a "weak" streamer case).

Having identified the relevant timescales, one can make a more quantitative estimate for the importance of the DITG shearing. However, such a calculation requires a specific model for the DITG spectrum. One way of estimating this is to note that as the DITG turbulence is driven by the temperature gradient, an upper bound for the DITG saturation level is roughly at a mixing length level given by

$$T_q = \frac{\tilde{T}_i}{T_{i0}} = \frac{1}{qL_{Ti}} \tag{38}$$

where $L_{Ti} = -d\ln T_{i0}/dx$ (L_{Ti} rather than L_n is used because the mode is driven unstable by the ion temperature gradient). One can then use quasilinearly relate the potential fluctuations to the temperature fluctuations via a simple model for curvature-driven DITG turbulence which gives

$$|\phi_q|^2 \simeq \frac{1}{q^2 L_B L_{Ti}} \tag{39}$$

. With this model of the DITG spectrum, one can at last estimate the ratio of γ_{lin}/γ_D via:

$$\gamma_D \sim \frac{\rho_e^2 v_{Te}^2}{\gamma_{lin}} \sum_q q^4 |\phi_q|^2 \sim \frac{\rho_e^2 v_{Te}^2}{\gamma_{lin}} \frac{\bar{q}^2}{L_B L_{Ti}} \tag{40}$$

so that

$$\frac{\gamma_{lin}}{\gamma_D} = \left(\frac{\sqrt{L_B L_{Ti}} \gamma_{lin}}{v_{Te}} \right)^2 \frac{1}{(\bar{q}\rho_e)^2} \simeq \frac{M}{m} \left(\frac{k_\theta \rho_e}{\bar{q}\rho_s} \right)^2 \frac{\eta_e - \eta_e^c}{\tau \eta_i} \tag{41}$$

, where $\eta_i = L_n/L_{Ti}$. In the above estimates, the characteristic wavenumber of the DITG turbulence is given by $\bar{q}$ and the fact that for curvature-driven ETG modes, the linear growth rate can be written as $\gamma_k \simeq \left(v_{Te}/\sqrt{L_n L_B} \right) k_\theta \rho_e \sqrt{\left(\eta_e - \eta_e^c\right)/\tau}$ has been used; $\tau = T_{e0}/T_{i0}$.

As described in the introduction, there are two particularly significant cases of structure formation in ETG turbulence, as they are believed to be the most likely sources of experimentally relevant levels of electron thermal transport. These are:

(1) large-scale streamers, which are observed in simulations to have $k_\theta \rho_e \simeq 0.1$
(2) electromagnetic effects, which may drive an inverse cascade of energy, causing energy to accumulate at collisionless electron skin depth $\delta_e = c/\omega_{pe}$ scales, such that $k_\theta \rho_e \simeq \rho_e/\delta_e = \sqrt{\beta_e}$

In either case, the shearing from DITG modes with $\bar{q}\rho_s < 1$ will still be weak; for instance, it is generally found that in simulations of curvature-driven ITG turbulence that the spectrum peaks near $\bar{q}\rho_s \simeq 0.1$. However, consideration of shorter wavelength modes (such as CTEM modes), which can produce fluctuations with $\bar{q}\rho_s \simeq 1$ would then suggest a shearing ratio for streamers

$$\frac{\gamma_D}{\gamma_{lin}} \simeq \left(\frac{q\rho_s}{k_\theta \rho_e} \right)^2 \frac{m}{M} \frac{\tau \eta_i}{\eta_e - \eta_e^c} \simeq 100\,(q\rho_s)^2 \frac{m}{M} \frac{\tau \eta_i}{\eta_e - \eta_e^c} \tag{42}$$

or (assuming $\beta_e \sim 10^{-2}$)

$$\frac{\gamma_D}{\gamma_{lin}} \simeq \frac{(q\rho_s)^2}{\beta_e} \frac{m}{M} \frac{\tau \eta_i}{\eta_e - \eta_e^c} \simeq 100\,(q\rho_s)^2 \frac{m}{M} \frac{\tau \eta_i}{\eta_e - \eta_e^c} \tag{43}$$

for δ_e-scale ETG fluctuations. In either case, it is clear that the shearing ratio could approach unity for some parameters (such as a weak deviation from marginality for the ETG modes), particularly when one notes that one may have strong CTEM fluctuations even for $q\rho_s \geq 1$.

Thus, it seems that in general while the shearing of ρ_e scale ETG by DITG is fairly weak (i.e. $\gamma_D << \gamma_{lin}$), the shearing due to short-wavelength DITG modes could have a significant impact on larger ETG structures, such as streamers on scales greater than ρ_e. This result confirms the basic intuition that for suppression by a shear flow to be effective, the scale of the turbulence or structure must be close to the scale of the shear flow[46]. It should be noted that while these DITG fluctuations are not generally considered the primary sources of turbulent transport (and thus often neglected), they constitute the relevant shearing field for the ETG turbulence and structures. This result is particularly important for ETG streamers as it could significantly impact their saturation level and spatial structure, and thus the overall relevance of ETG turbulence as a source of experimentally relevant electron thermal transport. Thus, ETG modes should be studied in the presence of a CTEM (or other short-wavelength component of DITG turbulence) background. In this regard, it is important to note that the shearing effect depends explicitly on mass ratio, therefore any simulations which use artificially high values of m/M to study these interactions must take extra care in quantifying the observed scalings with the mass ratio range explored. In addition, this effect introduces a new way for geometry to affect electron transport, as the shearing can arise from physics such as trapped particles, the population of which has a strong radial dependence.

3.2 DITG profile modulation effects on ETG turbulence

In addition to direct interactions between the velocity fields associated with coexisting ETG and DITG turbulence, there is at least one more cross-field interaction of interest: the convection of electron temperature fluctuations by the DITG turbulence. The impact of this interaction will have a somewhat different character than those of the previous discussions, as the ρ_s scale convection of T_e by DITG modulations will appear as modulations of L_{Te}, or equivalently, $\eta_e = L_n/L_{Te}$, to ETG modes. Such modulations of η_e represent an effective modulation of the ETG growth rate, which scales as $\gamma^{ETG} \propto \sqrt{\eta_e - \eta_e^c}$, where η_e^c represents a critical value of η_e needed for instability. The effective modulation of equilibrium parameters for small-scale fluctuations due to convection by a larger-scale turbulent spectrum has been previously investigated by Itoh and Itoh and co-workers using a general model of renormalized multi-scale turbulence [25,26]; here, we focus specifically on the effects of DITG-induced ∇T_e modulations on ETG turbulence via a different approach then was used in Ref. [25] and [26]. Specifically, we again exploit the fact that the DITG time scale is much slower than the ETG time scale, and treat the problem in the context of a wave-kinetic description of the ETG turbulence. One can write $\eta_e = \eta_e^0 + \delta\eta_e$, where $\delta\eta$ is the effective modulation due to the DITG turbulence, and we assume $\delta\eta_e/\eta_e^0 << 1$. Linearization of the wave-kinetic equation (Eqn. 34) provides:

$$R^{-1}\left(\Omega_q\right)\delta N_q = 2\frac{\partial\gamma_k}{\partial\eta_e}|_{\eta_e=\eta_e^0}\ \delta\eta_q\langle N\rangle \tag{44}$$

where $R\left(\Omega_q\right)$ is defined in Eqn. 37, and we have expressed $\delta\eta_e$ as $\delta\eta_e = \sum_q \delta\eta_q \exp\left(i\left(\vec{q}\cdot\vec{x} - \Omega_q t\right)\right)$.

We can then use quasi-linear theory to write the evolution equation for $\langle N\rangle$ as

$$\frac{\partial\langle N\rangle}{\partial t} = 2\left(\gamma_k + \gamma_{NL}\right)\langle N\rangle + O\left(\langle N\rangle^2\right) \tag{45}$$

$$\gamma_{NL} = 2\left(\frac{\partial\gamma_k}{\partial\eta_e}|_{\eta_e=\eta_e^0}\right)^2 \sum_q R\left(\Omega_q\right)|\delta\eta_q|^2 \tag{46}$$

Since $\gamma_k \sim \left(\eta_e - \eta_e^c\right)^{1/2}$, and one can estimate $R\left(\Omega_q\right) \sim 1/2\gamma_k$, the ratio of γ_{NL} to γ_k can be estimated as

$$\frac{\partial\gamma_k}{\partial\eta_e}|_{\eta_e=\eta_e^0} = \frac{\gamma_k}{2\left(\eta_e^0 - \eta_e^c\right)} \tag{47}$$

$$\rightarrow \gamma_{NL} \simeq \frac{\gamma_k}{4\left(\eta_e^0 - \eta_e^c\right)^2}\sum_q |\delta\eta_q|^2 \tag{48}$$

$$\Rightarrow \frac{\gamma_{NL}}{\gamma_k} = \frac{\sum_q |\delta\eta_q|^2}{4\left(\eta_e^0 - \eta_e^c\right)^2} = \frac{1}{4}\left(\frac{|\delta\eta_e|}{\eta_e^0 - \eta_e^c}\right)^2 \tag{49}$$

Thus, when the magnitude of the DITG modulations of η_e is comparable to the deviation of η_e^0 from the critical value η_e^c (i.e. the deviation from marginality), the gradient modulation effect will be important. Note that $|\delta\eta_e| = \sqrt{\sum_q |\delta\eta_q|^2}$ is the RMS amplitude of the gradient modulations, and inherently positive (reflecting the statisical averaging used in deriving Eqn. 49). One can estimate the magnitude of the fluctuations through a mean-field theory of DITG turbulence; it should also be straightforward to calculate the modulation amplitude using existing numerical simulations. Writing $|\delta\eta| = \alpha\eta_e^0$ (where $\alpha \leq 1$), Eqn. 49 shows that the effect of even these small pertubations could be quite significant as:

$$\frac{\gamma_{NL}}{\gamma_k} \propto \left(\alpha\frac{\eta_e^0}{\eta_e^0 - \eta_e^c}\right)^2 \tag{50}$$

It is important to note that the preceding analysis implicitly assumes that the net deviation from marginality $\eta_e^0 + \delta\eta_e - \eta_e^c$ is always greater than zero; that is, that the modulations of η_e are never strong enough to stabilize the ETG modes (which occurs when the net deviation is negative). However, common sense suggests that such a situation is entirely possible. One can also turn this caveat around, and note that there could just as easily be a situation in which the equilibrium profile indicated ETG stability, but fluctuations of η_e could *non-linearly* excite the ETG turbulence; in this case, one would find *sub-marginal* ETG turbulence. Such a situation would most likely induce highly intermittent or "bursty" behavior in the electron thermal flux, as η_e rose above or fell below the critical level for instability. Application of ideas from investigations of self-organized criticality [47,48] (i.e. the dynamics of bursty transport arising from a profile fluctuating around a critical gradient) could certainly prove useful in this context. While both are interesting questions, treatment of these issues would require a more sophisticated analysis which is beyond the scope of this letter. We also note that the scale separation between the DITG and ETG turbulence suggests that the modulations of η_e could induce significant nonlocal behavior in the ETG dynamics, as the DITG modes would allow coupling of the ETG dynamics across many ρ_e. Note that numerical investigation of these issue would require running simulations of ETG turbulence for many *DITG* space and timescales, as the induced burstiness and non-locality of the ETG turbulence will be on DITG scales.

4 Necessary Conditions for Experimentally Relevant Streamer-Driven Transport

As noted in the introduction, streamers and ETG turbulence have become popular explanations for not only the residual electron heat transport in internal transport barriers where the particle and ion thermal transport are suppressed (termed hereafter an ion ITB), but also sometimes for the bulk of the plasma. However, for such an explanation to be satisfactory, three critical issues must resolved. They are

(1) Do the parameters which correspond to ion ITBs favor the formation of *stable* ETG streamers?
(2) If a stable streamer does form in an ion ITB, is the expected transport comparable to that seen in experiment?
(3) If a stable streamer forms in a region where ITG or TEM turbulence also exists, is the expected streamer-driven transport large enough to dominate the ITG/TEM-driven transport?

To resolve the first issue, one might note that not only must streamers form in ion ITBs for the theory to succeed, but that streamer formation should also be *suppressed* for parameters corresponding to suppression of anomalous electron thermal transport, i.e. an electron ITB. From a theorist's simplified perspective, one might *roughly* characterize the conditions for formation of an ion ITB as weak or "mildly" negative magnetic shear $\hat{s}$, and moderate values of $\alpha = -Rq^2 d\beta/dr$, where q is the safety factor and $\hat{s} = rd\ln q/dr$, while electron ITBs form for stronger negative shear ($\hat{s} \sim -1$) and larger values of α (this crude characterization ignores many potentially important factors, such as the heating mechanism and profile). Computational studies by Jenko et. al., and more recently by Kendl [49], suggest that the linear growth rate for ETG turbulence essentially favors streamer formation in a "band" in $\hat{s} - \alpha$ space (see, e.g. Fig. 3 of Ref. [49]). As discussed in Sec. 2.4, nonlinear simulations seem to support some of this picture (i.e. there seems to be uniform agreement that low or negative shear leads to low transport levels, but the nessecary conditions for high transport (as opposed to the observation of streamers) remain an open question). A natural question to ask is whether this band overlaps the region of $\hat{s}-\alpha$ space one might associate with ion ITBs. If there is little or no overlap, then one must question whether streamers can explain the anomalous electron transport in these situations.

It is also important to determine whether the streamer is stable in this region. As shown in the previous section, the streamer stability depends crucially upon the damping mechanisms of the sidebands and K-H mode. One should note that while the previous discussion implicitly assumed that the perturbations modes all had a coherent damping rate, there could be more complex nonlinear saturation mechanisms of the perturbation as well. Considering previous studies of nonlinear ITG dynamics, it is clear that one should also consider whether the K-H mode could itself become nonlinearly unstable and breakup, i.e. suffer a so-called "tertiary" instability [50]. One could easily imagine that there is a critical amplitude for the K-H mode, after which it itself begins to breakup, in which case one could view the whole process (streamer $\rightarrow$ K-H mode $\rightarrow$ tertiary instability) as the first few steps in the development of broadband turbulence. On the other hand, if the K-H mode saturates below this critical value, then it may be reasonable to assume that the transport is driven by the streamer mode under consideration. In addition to these "self-saturation" issues, one must also consider whether the streamer will be stable in the presence of any DITG turbulence, as described in Sec. 3. One must therefore have not only a thorough understanding of the streamer stability and saturation level, but also the stability of the K-H mode.

Understanding the streamer saturation level is also crucial to answering the second and third questions, as the streamer transport is directly proportional to its saturation level. In particular, for an analytic theory of streamer transport to be considered successful, the transport must (in the language of a popular children's story) not be so small as indicated by mixing-length type estimates, nor too big as the simplistic nonlinear analysis suggests, but "just right." This requirement constitutes a specific test for theories of streamer-driven transport to meet. Resolving the third issue may be particularly challenging, in that it is has previously been assumed the the inherent electron thermal transport estimates one arrives at from considerations of ITG/TEM turbulence have generally been considered sufficient for explaining the bulk electron heat transport. Therefore, it is not obvious how one can self-consistently invoke ETG turbulence as the source of the electron transport, while claiming that the particle and ion thermal transport are due to ITG/TEM modes. The findings of Sec. 3 which clearly demonstrates the impact ITG and (especially) TEM modes will have on large-scale ETG structures makes the interpretation of ETG turbulence as a dominant source of electron thermal transport all the harder. If the final answer is that streamers (or other large-scale structures) cannot conclusively be shown to result in larger transport, one is left with explaining the inital observations of high anomalous electron thermal transport in cases where the ion and particle transport have been suppressed. One possibility may be short-wavelngth TEM modes, which would be more able to survive in the presence of large-scale shear flows which would suppress longer wavelength ITG turbulence.

5 Conclusions

A complete understanding of the underlying causes of anomalous electron thermal transport in magnetic confinement devices remains an outstanding challenge for the fusion community. The ETG mode has been proposed to be a potential source of this transport, by driving a heat flux much greater than simple mixing length estimates would suggest via various nonlinear mechanisms. Recently, one of the most prominent mechanisms has been that of ETG-driven streamers, which have a much greater radial correlation length than simple expectations would suggest, and which may also saturate at higher levels than mixing length estimates would suggest. In this paper, we have reconsidered the stability of an array of "stacked" streamers to K-H breakup in the context of the Hasegawa-Mima equation. It was shown that there is a minimum intensity for streamer breakup, determined by the frequency mismatch of the streamer and perturbation sidebands. It was also demonstrated that when ad-hoc linear growth and damping rates are included, there is still a minimum streamer intensity needed for breakup. The issue of streamer saturation was also reconsidered, as previous calculations of streamer saturation [19] were demonstrated to be internally inconsistent. Contrary to previous assertions, it was demonstrated that the streamer saturation level is determined by balancing the nonlinear growth rate of the KH mode against damping mechanims (both linear and nonlinear) of the KH mode, and *not* against the linear growth rate. This problem was demonstratrated to be conceptually analagous to the issue of coherent zonal flow generation by a "pump" drift-wave and two sidebands, where it is well known that the saturation level of the pump is set by the damping rate of the zonal flow. We note that differences in magnetic geometry and parallel dynamics, which will strongly influence the KH damping rate, may explain some of the significant differences observed by various nonlinear simulations of ETG turbulence.

The impact of DITG modes on ETG turbulence was also studied via simple models. It was found that while the random shearing of "generic" ρ_e scale ETG turbulence by DITG modes was weak, shearing of large-scale streamers and collisionless skin-depth fluctuations by short-wavelength ($\bar{q}\rho_s \simeq 1$) DITG modes will be a significant effect. This result should also apply to other large-scale structures such as ETG-driven zonal flows (calling into question the results of Li and Kishimoto [40], who argued that ETG-driven zonal flows could affect the DITG dynamics, but did not include the DITG shearing effect discussed here) or zonal magnetic fields [20,51]. Shearing of ETG-driven zonal flows and fields (which may regulate the levels of ETG turbulence) by DITG turbulence provides an additional saturation / limiting mechanism for these zonal modes beyond the collisional damping effects discussed by Kim *et al.* [38]. We emphasize the importance of DITG shearing of streamers because they represent a prominent potential mechanism for allowing ETG to drive experimentally relevant levels of transport. Therefore, their suppression directly impacts the status of ETG as a relevant source of significant transport. It is also important to note that it is the short-wavelength portion of the DITG spectrum which provides the relevant shearing field. This fact may have important ramifications for understanding transport physics in the presence of transport barriers, as these short-wavelength modes will be less affected by the presence of the equilibrium shear flow than the larger scale DITG modes. In addition, a primary source of such short-wavelength DITG modes (such as the CTEM) will be trapped electrons, which suggests that the importance of DITG shearing will vary with minor radius in the confinement device (e.g. as the fraction of trapped electrons increases with normalized radius, DITG shearing effects should become stronger). In addition, a novel mechanism for cross-scale coupling has been detailed, in which the DITG induced fluctuations of electron temperature gradient are manifested as a nonlinear modulation of the ETG growth rate. This effect was found to scale as $\left(\delta\eta_e / \left(\eta_e^0 - \eta_e^c\right)\right)^2$, which can be quite significant. What is particularly intriguing about this effect is that it can work to *enhance* the ETG intensity level, and *oppose* the effect of random shearing by the DITG turbulence. Understanding the competition between these effects would be particularly interesting for streamers and other large-scale ETG structures. Moreover, these results suggest that ETG models must be implemented in the context of a specific DITG background. Finally, we retiterate that while the effectiveness shearing of ETG turbulence by DITG modes will depend upont the ion - electron mass ratio, the η_e modulation effect *does not*, and therefore any numerical simulations of ETG-DITG interactions must take care when using artifical mass ratios so as not to bias the importance of one effect over the other.

The analysis also points towards a number of future inquiries. First, a better understanding of the dynamics of the “isolated burst” streamer is clearly needed. Investigations of this will be quite challenging from either an analytic or computational standpoint, as one must rigorously define what an “isolated burst” streamer is, and identify the proper framework (most likely probabilistic) for analyzing such structures. Second, the simple considerations of streamer stability and saturation presented here should be considered using a framework with multiple fluctuation fields and geometrical effects included. A particularly clear question for this problem is understanding how including parallel dynamics might impact the results considered here. Also crucial is developing a better understanding of the parameter space which represents streamer generation, and how this space overlaps with experimental observations of anomalous electron transport. Finally, the considerations of ETG-DITG interactions suggest a number of interesting avenues for future study, such as the trapping of ETG wavepackets in ITG turbulence, and ways to *feasibly and self-consistently* include the effects of DITG modes on ETG turbulence in numerical simulation.

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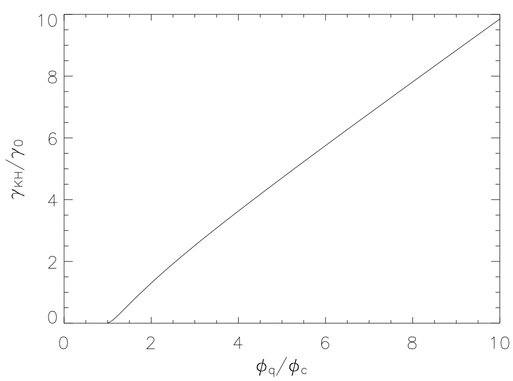
Figure Captions

Fig. 1. Maximized growth rate of K-H perturbation as a function of ϕ_q/ϕ_c.



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