Novel States of Pre-Transition Edge Turbulence Emerging from Shearing Mode Competition

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Abstract. A novel model handling zonal flow, geodesic acoustic mode (GAM), and turbulence self-consistently as a predator-prey system with multiple frequency shearings is introduced. ZF with finite frequency has different shearing relation from that with zero frequency depending to their auto-correlation times. Splitting ZF broadband spectrum into the two modes of wave populations enables us to state different shearing weights to the turbulence contributions of the ZFs. We define states with no ZF and GAM states as L-mode-like state, with ZF and without GAM as ZF-only state, with GAM and without ZF as GAM-only state, and both with ZF and GAM as the coexisting state. Since the coexisting state does not appear in the minimal model, mode-competition effects are introduced. We introduce one which originates from higher order perturbation of wave actions. The model exhibits a sequence of transition between various roots as the driving flux increases. In some chosen parameters, bi-stability is evident, which suggests the origin of the hysteretic behavior in the turbulence intensity field during power ramp up/down studies. In the presence of noise due to ambient turbulence offers a novel and interesting mechanism to explain the bursts and pulsations observed in the turbulence field prior to the L-H transition.

1. Introduction

Understanding the L-H transition requires a thorough comprehends of pre-transition turbulence [1]. It is now well established that edge turbulence has at least two constitutions, namely primary modes with cause transport and secondary shearing modes (i.e. zonal flow, GAM), and that the turbulence self-regulates via several shearing feedback loops. Both GAMs and zonal flows frequently have been detected in tokamak edge turbulence and have been observed to respond to changes in plasma conditions and proximity to the L-H transition.

There are now many observations of changes in the relative populations (both amplitude ratio and profile) of shearing modes while heating power increases approaching the transition [2,3,4]. In DIII-D experiments, it is suggested that transition from the GAM to ZF may help trigger L-H transition. Due to change of direction of NBI with co-injected power to balanced ones, a observed GAM peak in zonal flow spectrum decays and zero-mean-frequency zonal flow established just before a sudden L-H transition, i.e. transition from turbulent state to the quiescent steady state in a very short time scale [2]. On the other hand, in ASDEX-Upgrade experiments, strong dependence of GAM amplitude on turbulence strength is found, while little sign for the transition from GAM to ZF has appeared through the L-H transition [3]. This may indicate the GAM is just an easily visible secondary signature of the turbulence. Here these are accompanied by unusual phenomena such as bursts, pulsations, etc in turbulence. Furthermore, in LH-2A experiments, a mixture of nearly zero frequency ZF and finite frequency GAM peaks is observed, which is referred as to the coexisting state [4], while the previous experiments, in DIII-D or ASDEX-Upgrade, shows a single peak of zonal flow broadband spectrum through L-H transition.

Taken together the observations suggest the need to understand the dynamics of GAM and ZF co-existence and mode competition, and how this competition impacts the qualitative state of the turbulence. However, the observations alone have not fully clarified the GAM's role in shear suppression and possible energy transfer from zonal flows and to turbulence. Theory is necessary to illuminate these questions. Hence here we report on recent results from theoretical studies directed at these questions. A major focus of this work is the extension of the familiar predator-prey model for shears and primary modes to treat the case of multiple predators. The model predicts fundamentally new states of turbulence.

While zonal flows are stationary and thus exert coherent shears, GAMs propagate radially [5] and account of polarization current effects [6]. GAM propagation thus likely reduces the GAM shearing efficiency, since the GAM-drift wave coherence time $\tau_{ac} = \left|\Delta q(v_{gr,GAM} - v_{gr}(k))\right|^{-1}$ is smaller than the ZF-drift wave coherence time. Here Δq is the spatial bandwidth of the GAM shearing packet. This implies that a broadband GAM frequency shearing field is best characterized by *the shearing partition ratio* $\eta \equiv \tau_{ac,\omega} E_{\omega} / (\tau_{ac,\omega} E_{\omega} + \tau_{ac,0} E_0)$, where $E_{0,\omega}$ and $\tau_{ac,0,\omega}$ are the ZF and GAM energies and auto-coherence times, respectively. Note that η is set by *both* coherence times and the energies, and not simply by the ratio of shearing intensities. This issue has often been missed in previous analysis regarding GAM's turbulence suppression effects.

The reminder of this paper is the following. In Sec. 2 we introduce the minimal multiple shearing predator-prey model to describe interplay among turbulence, ZF, and GAM. In Sec. 3, we discuss why the minimal model is not enough. Here we introduce mode competition effect and thus formulate the model with the nonlinear effects. We also discuss the possible stability states in the model. In Sec. 4 we briefly discuss the stability analysis around possible fixed points. Here we find the bi-stable region of states, and thus discuss the relation of the bi-stability to the hysteretic behavior of turbulence intensity. In Sec. 5 we conclude this paper and remark on some thoughts.

2. A Minimal Multiple Shearing Predator-Prey Model.

Here we start from the well known wavekinetic equation [7] for drift wave action $N_k \equiv (1 + k_\perp^2 \rho_s^2)\left|\tilde{\phi}^2\right|$ coupling with the linear fluid ZF/GAM model [8] consisting of zonal flow velocity $U \equiv \langle v_E \rangle$, anisotropic up-down asymmetric pressure perturbation $G \equiv \langle p \sin\theta \rangle$, and anisotropic up-down symmetric parallel velocity perturbation $V \equiv \langle v_{||} \cos\theta \rangle$,

$$\frac{\partial N_k}{\partial t} + \frac{\partial \omega_k}{\partial \mathbf{k}} \cdot \frac{\partial N_{\mathbf{k}}}{\partial \mathbf{x}} - \frac{\partial \omega_k}{\partial \mathbf{x}} \cdot \frac{\partial N_{\mathbf{k}}}{\partial \mathbf{k}} = 0, \tag{1}$$

$$\frac{\partial U}{\partial t} = -q_r^2 \frac{c^2}{B^2} \int d^2 \underline{k} \frac{k_\theta k_r}{(1 + k_\perp^2 \rho_s^2)^2} N_{\underline{k}} - \gamma_{damp} U - \frac{2a}{n_{eq} R} G, \tag{2}$$

$$\frac{\partial G}{\partial t} = (\frac{5}{3} + \tau) p_{eq} \frac{a}{R} U + (\frac{5}{3} + \tau) p_{eq} \frac{a}{qR} V - \gamma_{LD} G, \tag{3}$$

$$\frac{\partial V}{\partial t} = -\frac{a}{n_{eq} qR} G, \tag{4}$$

where q_r is radial wave number of zonal flow components, $\omega_k = k_\theta V_* / (1 + k_\perp^2 \rho_s^2)$ is drift frequency, $V_* = c_s \omega_{ci}^{-1} L_n^{-1}$ is diamagnetic velocity, a and R is minor and major radius, respectively, $\gamma_{\rm damp}$ is collisional damping of zonal flow, $n_{\rm eq}$ and $p_{\rm eq}$ (and $T_{\rm eq}$) is equilibrium density and pressure (and temperature) profile, respectively, τ is T_e/T_i, $\gamma_{\rm LD}$ is the Landau damping rate of GAM. Through quasilinear treatment and discussion about shearing regarding the auto-correlation times [6] we yield a time evolution of turbulence intensity N as

$$\frac{\partial N}{\partial t} = \gamma_L N - \Delta\omega N^2 - \alpha N U^2, \tag{5}$$

where γ_L is a growth rate of turbulence intensity, which can be estimated from results of simulations or experiments by using $\gamma_L = \gamma(R/L_T - R/L_{T,crit})$, where $R/L_{T,crit}$ is the linear critical temperature gradient assuming the turbulence is driven by ion temperature gradient (ITG) mode, γ is a reference growth rate, and $\Delta\omega$ is a nonlinear damping rate of turbulence. Here α is a coupling parameter between turbulence and zonal flows which is determined by the shearing relation depending on mode frequencies. However, here zonal flows have two different eigenmode with zero and finite frequencies, i.e. *multiple frequencies*. Thus α cannot be determined easily. Note that Ref. [9] discusses a multiple shearing predator-prey model, consisting of turbulence, ZF, and mean flow shear $\langle V_E \rangle'$.

To reproduce shearing effects of zonal flows with multiple frequencies, we separate U by expanding Eqs. (2) - (4) by Fourier frequency modes and retain up zero-frequency and high-frequency modes. Here we assume zonal flows spectrum consist of the zero frequency mode (ω=0) and high frequency modes ($\omega=\pm\omega_G$) populations. We assume time derivatives of G and V obeys eigenmode ratios, that is $\partial_t U : \partial_t G : \partial_t V = \omega_G : 0 : -\omega_{GAM}$ for a mode with ω=0 and $\partial_t U : \partial_t G : \partial_t V = \omega_{GAM} \pm i\omega_G : \omega_{sound}$ for modes with $\omega=\pm\omega_G$, where $\omega_{GAM} = \sqrt{2(5/3+\tau)T_{eq}}\,(a/R)$, $\omega_{sound} = \sqrt{(5/3+\tau)T_{eq}}\,(a/qR)$, and $\omega_G = \sqrt{\omega_{GAM}^2 + \omega_{sound}^2} = \sqrt{2(5/3+\tau)T_{eq}/(1+2q^2)}\,(a/R)$. We assume higher temperature plasmas so that fast (GAM) time scale can separate from slow (transport) time scale. Finally we obtain the following *minimal* multiple shearing predator-prey model with one prey and two predators, consisting of a time evolution of the turbulence intensity N, which expands $\alpha U^2 = \alpha_0 E_0 + \alpha_\omega E_\omega$ in Eq. (5), and those of the zonal flow energy $E_0 = |U_0{}^2|$ and the GAM energy $E_\omega = |U_{+\omega}{}^2| + |U_{-\omega}{}^2| = 2|U_\omega{}^2|$,

$$\frac{\partial N}{\partial t} = [\gamma_L - \Delta\omega N - \alpha_0 E_0 - \alpha_\omega E_\omega] N, \tag{6}$$

$$\frac{\partial E_0}{\partial t} = A_0(\alpha_0 N - \gamma_0) E_0, \tag{7}$$

$$\frac{\partial E_\omega}{\partial t} = A_\omega(\alpha_\omega N - \gamma_\omega) E_\omega, \tag{8}$$

where α_0 and α_ω are characterized by the ZF/GAM-drift wave coherence time, i.e. $\alpha_0 \sim \tau_{ac,ZF}$ and $\alpha_\omega \sim \tau_{ac,GAM}$. Note that $\tau_{ac,GAM} < \tau_{ac,ZF}$. γ_0 and γ_ω are dissipations of ZF and GAM. In the calculations, we find $\gamma_0 = \nu_{damp}$, where ν_{damp} is the collisional damping rate of ZF, while $\gamma_\omega \approx \nu_{damp} + \gamma_{LD}$, where we assume q>1 and thus combinations of the dissipations are so small. Thus $\gamma_0 < \gamma_\omega$ is satisfied. A_0 and A_ω are screening factors regarding q-value dependency, that is $A_0 = (1+2q^2)^{-1}$ and $A_\omega = 1 - A_0$.

However the minimal model cannot reproduce the coexisting state, because coexisting state of ZF and GAM cannot be defined. Based on the derived minimal multiple shearing predator-prey model, we investigate the stability of states of turbulence, ZF, and GAM. We calculate possible fixed points (N, E_0, E_ω), where $\partial_t N = \partial_t E_0 = \partial_t E_\omega = 0$. They are (i) a L-mode-like state (N_L, 0, 0), (ii) a ZF-only state ($N_0{}^*$, E_{0*}, 0), and (iii) a GAM-only state ($N_{\omega*}$, 0, $E_{\omega*}$), where $N_L = \gamma_L/\Delta\omega$, $N_{0*} = \gamma_0/\alpha_0$, $N_{\omega*} = \gamma_\omega/\alpha_\omega$, $E_{0*} = (1/C_0)(N_L - N_{*0})$, $E_{\omega*} = (1/C_\omega)(N_L - N_{*\omega})$, $C_0 = \alpha_0/\Delta\omega$, and $C_\omega = \alpha_\omega/\Delta\omega$. Analyses around the fixed points show that the ZF-only state is stabilized as long as $N_{0*}>N_{\omega*}$ is satisfied. This corresponds to the fact that without turbulence GAM is always damped by the Landau damping, while ZF resides without the collisional damping [10].

3. A Multiple Shearing Predator-Prey Model with Mode Competition.

In this section, we discuss the possible mechanism reproducing the coexistence in a multiple shearing predator-prey model. As shown in the previous section, the minimal model with only linear processes of ZF and GAM cannot reproduce the coexistence, because none define a mixture of states. Therefore some nonlinear dynamics between the predators, i.e. *mode competition*, is necessary. The competitive exclusion principle, which forbids the stable coexistence of two or more species making their livings in identical ways, is one of basic concepts in ecosystem community [11]. Though there are many candidates to facilitate the mode competition, here we examine on which originates from higher order perturbation of wave actions [12, 13]. Therefore turbulence mediation is essential in this case. Expanding N of Eqs. (7) and (8) in terms of E_0 and E_ω, we obtain a following multiple shearing predator-prey model with mode competition,

$$\frac{\partial N}{\partial t} = [\gamma_L - \Delta\omega N - \alpha_0 E_0 - \alpha_\omega E_\omega]N + (\text{h.o.t}), \tag{9}$$

$$\frac{\partial E_0}{\partial t} = A_0[\alpha_0 N(1-\gamma_{00}E_0 - \gamma_{0\omega}E_\omega) - \gamma_0]E_0\,, \tag{10}$$

$$\frac{\partial E_\omega}{\partial t} = A_\omega[\alpha_\omega N(1-\gamma_{\omega 0}E_\omega - \gamma_{\omega\omega}E_\omega) - \gamma_\omega]E_\omega\,, \tag{11}$$

where γ_{ij} ($i,j=0,\omega$) are nonlinear coupling parameters, which can be estimated from calculations of the higher order perturbation of wave action as

$$\gamma_{00} \cong \frac{1}{2}\tau_{ac,ZF}^2, \tag{12}$$

$$\gamma_{0\omega} \cong \frac{\tau_{ac,ZF}\tau_{ac,GAM}[(2+\varepsilon)\tau_{ac,GAM} + 3\tau_{ac,ZF}]}{2(\varepsilon\tau_{ac,GAM} + \tau_{ac,ZF})}, \tag{13}$$

$$\gamma_{00} \cong \frac{1}{2}\tau_{ac,GAM}^2 + \frac{1}{2}\tau_{ac,ZF}\tau_{ac,GAM}, \tag{14}$$

$$\gamma_{00} \cong \frac{\tau_{ac,GAM}^2[2\tau_{ac,GAM}^2 + (2+\varepsilon)\tau_{ac,GAM}\tau_{ac,ZF} + \tau_{ac,ZF}^2]}{2(\varepsilon\tau_{ac,GAM} + \tau_{ac,ZF})}, \tag{15}$$

where ε is a ratio of the spatial bandwidth of the GAM shearing wave packet to that of ZF shearing ones, $\varepsilon=\Delta q_{r,\mathrm{GAM}}/\Delta q_{r,\mathrm{ZF}}$. Higher order terms (h.o.t.) in N are dropped to simplify calculations.

This system represents a generalization of the intuitively appealing predator-prey model to the case of multiple shearing fields of different frequencies. A state of ZF and GAM co-existence appears only when *shearing mode competition* is addressed, in this case via higher order coupling through the turbulence. Our multi-predator/prey system has four nontrivial roots (fixed points: (N, E_0, E_ω)), i.e. (i) one with no shear flows (a L-mode-like state) (N_L, 0,

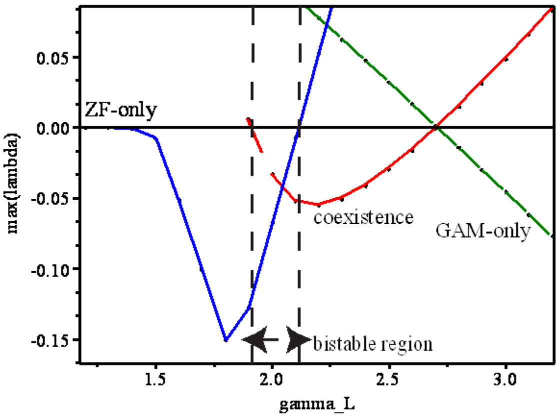

Fig. 1. Temperature gradient (γ_L) scan of maximum eigenvalues λ for the various equilibrium states. In the region $1.9<\gamma_L<2.1$, both ZF-only and the coexisting state are stable, thus establishing bistability.

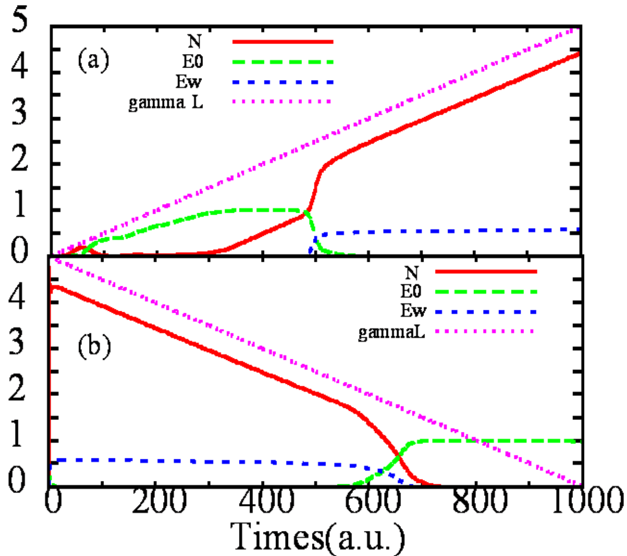

Fig. 2. Time evolution of N, E_0, E_ω, with artificial (a) increasing $\gamma_L(L_T^{-1})$ and (b) decreasing γ_L (L_T^{-1}).

0), (ii) a ZF-only state ($N_{0^*\mathrm{NL}}$, $E_{0^*\mathrm{NL}}$, 0), (iii) a GAM-only state ($N_{\omega^*\mathrm{NL}}$, 0, $E_{\omega^*\mathrm{NL}}$), and (iv) a newly found *state of ZF-GAM coexistence* ($N_{*0\omega\mathrm{NL}}$, $E_{0^*0\omega\mathrm{NL}}$, $E_{\omega^*0\omega\mathrm{NL}}$) .

4. Stability analysis, bistability, and its implementation.

Here we have investigated stability around the found fixes points in the multiple shearing predator-prey model with mode competition, i.e. dynamical system analysis [14]. The model exhibits a sequence of transitions between various roots as the driving flux and thus $\gamma_L(R/L_T-R/L_{T,\mathrm{crit}})$ increases. The precise sequence of states varies with system parameters (i.e. γ_{ij}). First we investigate a case with the following parameters: γ_{00}=1.0, $\gamma_{0\omega}$=2.0, $\gamma_{\omega 0}$=0.1, and $\gamma_{\omega\omega}$=1.5, (and thus $\gamma_{00}-\gamma_{\omega 0}>0$, $\gamma_{0\omega}-\gamma_{\omega\omega}>0$, and $\gamma_{00}\gamma_{\omega\omega}-\gamma_{0\omega}\gamma_{\omega 0}>0$). The other parameters are α_0=1.5, α_ω=1.0, $\gamma_{\mathrm{damp}}=10^{-4}$, q=1.0, and γ_{LD} = 1.0·exp($-q^2$). Figure 1 shows a sequence of transitions among ZF-only, GAM-only, and coexisting states with these parameters. Here the vertical axis represents the maximum of eigenvalues around corresponding fixed points, and thus the positive value shows unstable region, while the negative one shows stable. It is found that the ZF-only state is stabilized in weak turbulence region (γ_L<2.1), the coexisting state is in the region 1.9<γ_L<2.7, and the GAM-only state is in 2.7<γ_L. This indicates the GAM's shearing proportion η tends to goes up in the region with power ramp up above some critical, and reaches 1 in some region. Note that this picture is different that of usual L-H transition [15], because here we don't care for mean flow effects. Interestingly, bi-stability is evident, i.e. for some ranges of R/L_T-$R/L_{T,\mathrm{crit}}$ (here, 1.9<γ_L<2.2), both ZF-only (or GAM-only states) and ZF/GAM coexistence states are possible as shown in Fig. 1.

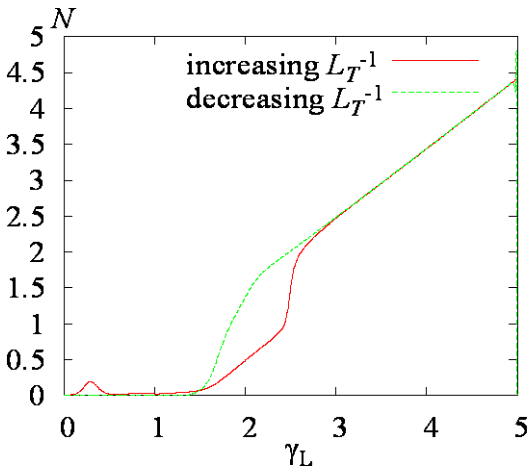

Fig. 3. Plots of evolution of turbulence intensity N versus temperature gradient (γ_L) in cases with induced ramp up/down of L_T^{-1}.

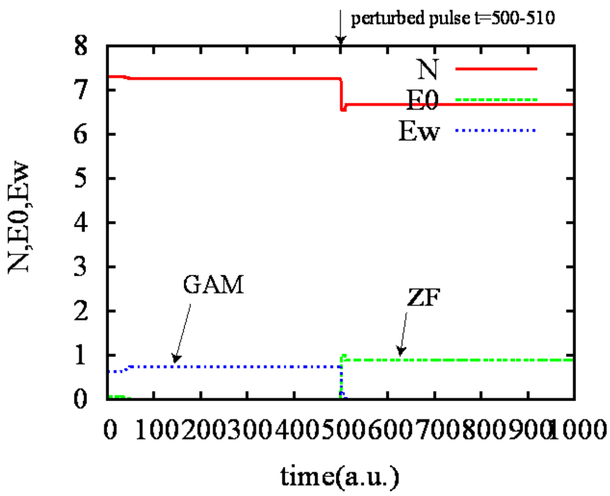

Fig.4. Temporal evolution of N, E0 and Ew with parameters as a bistability of ZF-only and GAM-only states is established. At t=500-510, artificial noise affected to turbulence field.

Multiple states coexistence in turn suggests the origin of the hysteretic behavior, discovered during power ramp up/down studies. Here we have compared cases with artificial increasing and decreasing L_T^{-1}, as seen in Fig. 2. In Fig. 2(a), as power ramps up, a transition of states from the ZF-only to the GAM-only state through the coexistence is seen at γ_L~2.5, where a bifurcation from the coexisting to the GAM-only state is seen in Fig. 1. On the other hand, in Fig. 2 (b), as power ramps down, the transition from the GAM-only state to the ZF-only state is found through the coexisting state around $2.5>\gamma_L>1.8$, which corresponds to the region where the coexisting state is stabilized in Fig. 1. Now we plot these evolutions of turbulence intensity N versus γ_L representing temperature gradient L_T^{-1} in Fig. 3. We find the hysteretic behavior of turbulence intensity N there. Note that we find a criterion that the bistability is established, i.e. $\alpha_\omega/\alpha_0<\gamma_{0\omega}/\gamma_{00}$. Therefore the bistability in shear field of low frequency and high frequency ZF is due to the different shearing effects.

Moreover, bistability in the presence of noise [16] (due ambient turbulence) offers a novel and interesting mechanism to explain the bursts and pulsations [3] observed in the turbulence field prior to the L-H transition. Fig. 4 shows an example that an artificial small perturbation can transfer states with the GAM-only to the ZF-only state. This can somehow explain the change of GAM to ZF state observed in DIII-D experiments. Here used parameters were set as the bistability of GAM-only and ZF-only is established. In principle, in bistability region, a resultant state is determined by a series of initial values or initial conditions. Therefore external force can change the equilibrium of the system.

Note that we have analytically calculated the stability of the system with the dynamical system analysis in any cases of the nonlinear parameters. We have here found that the GAM-only state or the coexisting state tend to be mostly stabilized in stronger turbulence region, in accordance with balances of ZF/GAM between self-suppression terms, i.e. diagonal coefficients, and mode competition terms, i.e. off-diagonal coefficients. Some exception that the ZF-only state is stabilized in whole turbulence region might occur when GAM's mode-competition effect to ZF is relatively weaker than GAM's self-suppression effect and ZF's mode-competition effect is stronger than ZF's self-suppression effect. In other words, there any energy drive to the GAM energy population can be absorbed into the ZF energy population through turbulence mediation, while usually any energy drive to the ZF energy population can transfer to the GAM energy population through turbulence mediation otherwise.

5. Conclusion and Remarks.

We have identified possible states of ZF/GAM/turbulence based on the multiple shearing predator-prey model with mode competition. Broadband shearing has its own coherence time as well as strength. Therefore we define the shearing ratio η, i.e. GAM shearing versus total (GAM+ZF) shearing quantities. Based on understandings of the GAM shearing, we have investigated the ZF/GAM interaction to construct a minimal predator-prey model with multiple shearings. The minimal predator-prey model consists of one prey turbulence and two predators, i.e. ZF with ω~0 and GAM with $\omega \sim \omega_{GAM}$. Since the minimal model cannot identify the coexistence of ZF and GAM, thus we consider one mechanism of mode competition via coupling higher order wavekinetics. Hereby we have found four states, a L-mode-like, a ZF-only, a GAM-only, and the coexisting states, as possible fixed points of the model. We have examined one case, and have found states and the sequence of progress selected by power ramp evolution and parameters. As power increases, the ZF-only state transfers to the GAM-only state through the coexisting state. We have found that bistability in shearing field is possible and thus jumps or transition between GAM and ZF states are possible. There are also seen a hysteretic behavior between cases with power ramp up and down, which originates from nature of the bistability.

Here we have several thoughts for experiments. First of all, fundamentally we should observe toroidal mode number n=0 spectrum in the space of k_r and ω to measure the GAM property. Determination of the correlation time shear in ω bands as well as energies is important to really estimate GAM's contribution to turbulence. As shown in Ref. [6], we have found that different shearing coefficients corresponding to the coherence time between GAM/ZF-drift wave packets can be expected. As well, it is useful to map η as functions of R/L_T-$R/L_{T,\mathrm{crit}}$ and r. This parameter can characterize the importance of the GAM as a function of power ramp and radial location.

The bistable property suggests the possibility if observed strong turbulence pulsations or bursts a symptom of bistability in ZF/GAM competition problem. Some moderate intensity of periodic pulsation can regulate bistability system to be synchronized to the periodic input noise/pulsation in a laser experiments with a bistability system [17, 18]. In turn, interesting comparison is "How moderate the pulsation is to reproduce the dithering-like oscillation of GAM and ZF?" Hereafter, one interesting question is how we control the intensity of pulsation and whether the change of the intensity could regulate the periodicity of ZF and GAM. The "noise" here is related to turbulence dynamics. It would be related to turbulence intensity and variability, i.e. avalanche interaction with the edge. The most reasonable way to handle noise would be to balance driving flux with transport, setting local gradient. So high noise burst would correspond to arrival of avalanche at the edge.

Another issue regarding the GAM propagation is to map of (k_r, ω) and then making $\partial\omega/\partial k_r$ contours. Survey of the group propagation of GAM as well as that of the phase propagation must be helpful to understand the GAM nonlocal dynamics. Bicoherence analysis can elucidate how the mode competition can be constructed and it might be helpful to expand our thoughts for the mode competition mechanism. We wonder if test for the bistability or hysteresis in η in power ramp up/down is possible. It is useful to examine possibility of evolution of $1/\tau_{\mathrm{c,turb}}$ and $\omega(k)_{\mathrm{GAM}}$ crossing over. Assuming edge plasmas, GAM frequency goes down as temperature goes down, while turbulence has finite frequency as it approaches the edge, therefore the GAM frequency peak can be degenerate with ZF when $1/\tau_{\mathrm{c,turb}} \sim \omega(\mathrm{k})_{\mathrm{GAM}}$ is satisfied. This can be another reason why the observed GAM is condensed at the edge region. Therefore observation of the crossing-over is important to understand the edge turbulence/ZF/GAM interplays.

To understand the comprehensive property of edge turbulence in terms of L-H transition, we need the following further works. First we need expand this to one dimensional model involving mean flow shear effects and maybe the GAM propagation. More thorough study of competition mechanism is required, i.e. mean flow shear can affect GAM shearing, and ZF shear also can affect GAM shear. Still we believe that including higher order expansion of

ZF/GAM energy the basic form in terms of self-suppression/mode-competition effects can keeps in the first order expansion, except for treatments of dissipations. That is, effective damping effects, collision or Landau damping, can be slightly reduced in strong turbulence region due to excitation of ZF/GAM energy, which originates from the ZF/GAM shearing effects to the ZF/GAM shearings. These processes should be carefully examined in future work. Especially, these effects might be important when the crossing-over of turbulence decorrelation time and GAM frequency occurs, as discussed above. We need to expand the predator model to *three* predators, including mean flow shear. As denoted above, the present portrait of turbulence intensity versus temperature gradient is different from the usual L-H transition picture, because here we do not mention the mean flow shearing effect on ZF/GAM shearing. Therefore mean flow must be another player in the mode competition figures.

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