J. Plasma Fusion Res. SERIES, Vol. 8 (2009)

Seesaw Mechanism in Turbulence-Suppression by Zonal Flows

Kimitaka ITOH[1], Sanae-I. ITOH[2], Masatoshi YAGI[2], Atsushi FUKUYAMA[3]

[1]*National Institute for Fusion Science, Toki, Gifu 509-5292, Japan*
[2]*Research Institute for Applied Mechanics, Kyushu University, Kasuga, Fukuoka 816-8580, Japan*
[3]*Department of Nuclear Engineering, Kyoto University, Kyoto 606-8501, Japan*

(Received: 1 September 2008 / Accepted: 20 November 2008)

Theory of non-local transport has been developed, taking an example of zonal flows (ZFs), the radial correlation length of which is longer than those for microscopic fluctuations. ZF, which is driven by fluctuations at one radius, can suppress fluctuations at distant radii. This mechanism induces new non-local interactions in turbulent transport. That is, strong fluctuations at particular radius can suppress fluctuations at different radius, via induction of ZFs. Stronger fluctuations suppress weaker fluctuations. This is called the seesaw mechanism via ZFs.

Keywords: no-local transport, transient transport, zonal flows, turbulence suppression, drift wave turbulence, nonlinear theory.

1. Introduction

Research of non-local and transit transport is an urgent issue in modern plasma physics. Experiments have reported the non-diffusive mechanisms in rapid response of transport between distant radii (see, e.g., recent report [1]). Simulations have demonstrated that transport barrier can be established while increasing linear growth rate of local instabilities [2]. These observations demonstrate that non-local interactions of turbulent fluctuations that are responsible for anomalous transport should have a key role in determining the transport in confined, high-temperature plasmas. Theory of non-local transport has been developed, based upon the statistical theory of plasma turbulence [3]. In this theoretical framework, global perturbations (which may be linearly stable) are shown to be excited by microscopic turbulence. Such a global perturbations have long radial correlation length and transmits the variation by its phase velocity, not by diffusive process. As a result of this, a change of microscopic turbulence at one radius propagates across the plasma column much faster than the expectation of diffusive response.

This new physics view awaits application to understand the non-local and rapid response in transport. Example of such nonlinearly-driven, meso-scale fluctuations is the zonal flow (ZF) [4]. ZFs grow extracting energy from microscopic fluctuations so as to reduce the turbulence and turbulent transport. Because the radial correlation length of ZF is longer than those for microscopic fluctuations, which are inducing turbulent transport, ZF, which is driven fluctuations at one radius, can suppress fluctuations at distant radii. Thus, the fluctuations can exchange energy over the distance that is much longer than autocorrelation length of microscopic fluctuations. This mechanism induces new non-local interactions in turbulent transport. That is, strong fluctuations at particular radius can suppress fluctuations at different radius, via induction of ZFs. Stronger fluctuations suppress weaker fluctuations. This is called the seesaw mechanism via ZFs. Owing to this mechanism, the turbulence transport is not determined by local parameters alone, but by parameters at far distance. The transient response is much faster than the process governed by diffusive processes.

2. Model

We employ a predator-prey model of DW-ZF system. Here, we notice that a zonal flow eigenmode (radial correlation length of which is chosen here as L) is excited by a large number of drift waves (radial correlation length is much shorter than L). The local growth rate and nonlinear damping rate (through like-scale nonlinearities) for drift waves vary in radius, and the scale length of variation can be of the order of L. In this case, the predator-prey model takes a form

author's e-mail: itoh@nifs.ac.jp

$$\frac{\partial}{\partial t} I(x) = \gamma(x) I - \omega_2 I^2 - \alpha\, E\, I \qquad (1)$$

$$\frac{\partial}{\partial t} E = \alpha\, E \frac{1}{2L} \int_{-L}^{L} dx\, I - \nu E \qquad (2)$$

where $I(x)$ is the intensity of DW, $\gamma(x)$ is the local growth rate, $\omega_2 I$ is the nonlinear damping rate of DW, E is the intensity of ZF, α is a coupling coefficient between DW and ZF and ν is the linear damping rate of ZF. (Intensities and are normalized to the kinetic energy density at the diamagnetic drift velocity.) Coefficients ω_2 and α can also vary in radius. However, we take them constant in radius, for the transparency of argument, without loosing the essence of the problem. The intensity of zonal flow E is constant within the correlation length L.

3. Seesaw Mechanism

This system describes that fluctuations at the location x are suppressed by zonal flow that is driven by fluctuations at the location x', $|x - x'| < L$. Stationary state is discussed in the following. From Eq.(1), we have

$$I = \frac{1}{\omega_2}\left(\gamma(x) - \alpha\, E\right) \quad \text{if} \quad \gamma(x) > \alpha E \qquad (3a)$$

and

$$I = 0 \quad \text{if} \quad \gamma(x) < \alpha E\,. \qquad (3b)$$

Equation (2) provides

$$\frac{1}{2L}\int_{-L}^{L} dx\, I = \frac{\nu}{\alpha} \quad \text{if} \quad E > 0 \qquad (4a)$$

and

$$E = 0 \quad \text{if} \quad \frac{1}{2L}\int_{-L}^{L} dx\, I < \frac{\nu}{\alpha}\,. \qquad (4b)$$

Thus, it describes the competition of fluctuations at different locations through the interactions of zonal flows. Consider the case that there two areas within a correlation length of the zonal flow (i.e., drift waves are strongly unstable in one area A, and are weakly unstable in the other area B). The level of zonal flow is enhanced by fluctuations in area A. Then the enhanced zonal flow suppresses the fluctuations in area B. The enhanced fluctuations in area A suppress fluctuations in the area B through exciting zonal flows. This is called seesaw mechanism in turbulent transport.

For explicit illustration, we take a parabolic model for the local growth rate, and take the origin at the minimum position (Fig.1):

$$\gamma(x) = \gamma_0 + \left(\gamma_1 - \gamma_0\right)\frac{x^2}{L^2}\,. \qquad (5)$$

We take the case of $\gamma_1 > \gamma_0$, and the opposite case is straightforward.

Substituting Eq.(5) into Eqs.(3) and (4), we obtain the following. Zonal flows are excited if collisional damping is weak:

$$\frac{1}{\omega_2}\left(\gamma_1 + 2\gamma_0\right) > 3\,\frac{\nu}{\alpha} \qquad (6)$$

In opposite case,

$$\frac{1}{\omega_2}\left(\gamma_1 + 2\gamma_0\right) < 3\,\frac{\nu}{\alpha}\,,$$

ZFs are not excited, and bare drift waves occurs.

We consider the case of weak collisional damping and ZF is excited. When the inhomogeneity of local growth exceeds the threshold,

$$\frac{1}{\omega_2}\left(\gamma_1 - \gamma_0\right) > 3\,\frac{\nu}{\alpha} \qquad (7)$$

fluctuations are suppressed ($I = 0$) in the region of weak instability

$$|x| < x_c\,, \qquad (8)$$

where the boundary x_c satisfies the condition

$$\left(1 - \frac{x_c}{L}\right)^2\left(1 + \frac{2x_c}{L}\right) = 3\,\frac{\nu}{\alpha}\,\frac{\omega_2}{\left(\gamma_1 - \gamma_0\right)}\,. \qquad (9)$$

In this case, fluctuations are suppressed completely in the domain $|x| < x_c$ although the region is linearly unstable against linear drift mode.

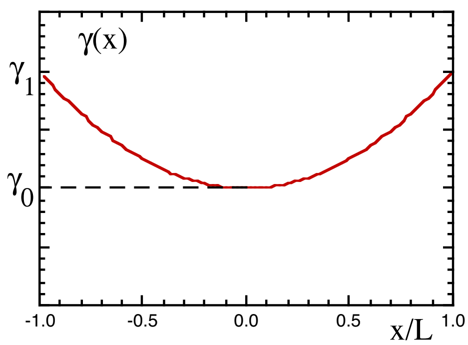

Fig.1: Model of radial distribution of the local growth rate

Profile of fluctuation intensity is shown in Fig.2 for the cases of

$$\frac{1}{\omega_2}\left(\gamma_1 - \gamma_0\right) = 6\,\frac{\nu}{\alpha} \quad \text{(strong inhomogeneity of drive)},$$

$$\frac{1}{\omega_2}\left(\gamma_1 - \gamma_0\right) = 2\,\frac{\nu}{\alpha} \quad \text{(weak inhomogeneity of drive)}$$

and

$$\gamma_1 = \gamma_0 \quad \text{(no inhomogeneity)}.$$

It is shown clearly that the turbulence intensity in the regime of weaker instability is suppressed if the growth rate increases at distance. In the case of strong inhomogeneity, the fluctuations are completely suppressed in the vicinity of the local minimum of the growth rate. In the moderate case, fluctuations are reduced in the entire region, but the suppression is not predicted. Figure 3 illustrates the profiles of the intensity of turbulent fluctuations (solid line), and zonal flow (dashed line), together with the profile of linear growth rate $\gamma(x)$ (dotted line). The competition of fluctuations leads to the quench of fluctuations in unstable domain.

This mechanism naturally induces the fast response at far distance. When the characteristics of turbulence at one radius are modified at an instance, then the influence occurs in the region (width L) directly via dynamics of zonal flows. This transmission of information does not need the diffusive propagation of change. Thus, fast transit response propagates across the plasma column. The study of dynamical problem will be discussed in separate article.

4. Summary

Novel non-local interactions of microscopic turbulence via zonal flow are investigated. Strong fluctuations at particular radius can suppress fluctuations at different radius, via induction of ZFs. This is called the seesaw mechanism via ZFs. Owing to this mechanism, the turbulence transport is not determined by local parameters alone, but by parameters at far distance. The threshold of turbulence suppression is formulated as a global condition. The transient response is much faster than the process governed by diffusive processes.

Acknowledgements

Discussions with P. H. Diamond, S. Inagaki, Y. Nagashima, and A. Fujisawa are cordially acknowledged. Work supported by the Grant-in-Aid for Specially-Promoted Research (16002005), by the Grant-in-Aid for Scientific Research (19360418) and by collaboration programme NIFS06KDAD005 and by collaboration programme of RIAM Kyushu University.

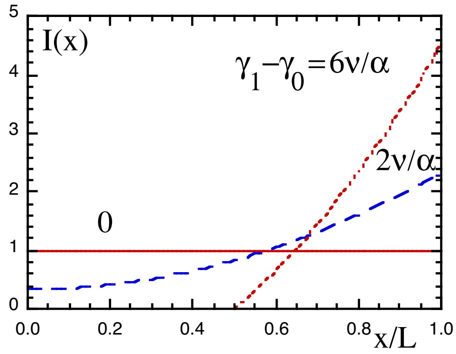

Fig.2: Profile of fluctuation intensity for $\left(\gamma_1 - \gamma_0\right)\,\omega_2^{-1} = 6\,\nu\,\alpha^{-1}$, $\left(\gamma_1 - \gamma_0\right)\,\omega_2^{-1} = 2\,\nu\,\alpha^{-1}$ and $\gamma_1 = \gamma_0$.

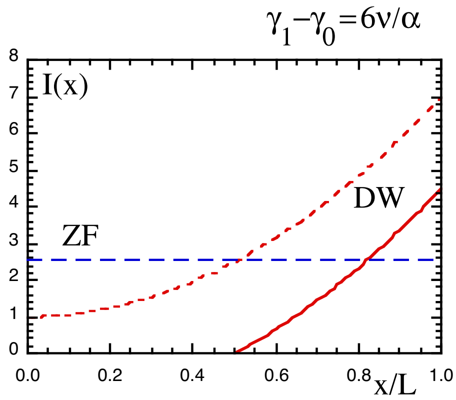

Fig.3: Profile of fluctuation intensity, zonal flow amplitude and local growth rate for the case of strong inhomogeneity. The fluctuations near the minimum of linear growth rate are quenched through competition with fluctuations in distant location.

References

[1] S. Inagaki, et al.: Plasma Phys. Control. Fusion **48** A251 (2006)
[2] M. Yagi, et al.: Plasma Phys. Contr. Fusion **48** A409 (2006)
[3] S.-I. Itoh, K. Itoh: Plasma Phys. Control. Fusion **43** 1055 (2001)
[4] P. H. Diamond, S.-I. Itoh, K. Itoh and T.S. Hahm: Plasma Phys. Control. Fusion **47** R35 (2005)