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Nonlinear processes of zonal flows near a plasma edge
プラズマ境界近傍における帯状流の非線形過程

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The new mechanism of the mean flow generation is presented, investigating the system which consists of turbulence, and stationary zonal flow (ZF) with considering the plasma edge effect. Based on the fluid model, the set of coupling equations among turbulence, ZF, and mean flow is derived by evaluating the perpendicular Reynolds stress with the wave-kinetic equation. The model of the plasma edge is proposed: the zero frequency components, ZF and mean flow, exchange the poloidal momentum with the flow in the scrape off layer (SOL) and becomes same with that in the SOL at the plasma edge. The effect of the plasma edge is introduced in the coupling equations as the boundary condition. The finite mean flow is obtained, whose value is comparable to the diamagnetic drift velocity.

1. Introduction

Since the discovery of the high confinement mode (H-mode) [1], the formation mechanism of the H-mode has been attracted much attention. The importance of a mean flow in the poloidal direction near the plasma edge is widely recognized [2]. The strong radial electric field is observed near the edge [3]. The generation mechanism of the mean flow has been studied theoretically [4]. The stationary zonal flow (ZF) has been observed during the L-H transition [5]. It becomes more and more important to understand the interaction among turbulence, ZFs and mean flow.

In this study, the new mechanism of mean flow generation is studied, analyzing the nonlinear coupling between turbulence and ZF near the plasma edge. Due to the momentum exchange across the plasma boundary, the net poloidal momentum can become finite in the plasma near the edge to generate a poloidal mean flow. In Sec. 2, the model of the generation of mean flow near the plasma edge is described. The summary and discussion are given in Sec. 3.

2. Model of Mean Flow Generation

The model equations are based on the fluid equations in the simple magnetic geometry (high aspect ratio, circular plasma) [6]. The nonlinear terms are focused on that from the perpendicular Reynolds stress, which is evaluated with the wave-kinetic equation. We consider the system that consists of turbulence and ZF near the plasma edge, and the mean flow is shown to be excited. The vorticity of the ZF is assumed to be the monotonic plane wave. The vorticity of the zero frequency components is written as

$$U = U_Z e^{iq_Z x} + U_Z^* e^{-iq_Z x} + U_{MF} \qquad (1),$$

where q_Z is the radial wavenumber of the ZF, and U_Z, U_{MF} are the vorticity of the ZF and mean flow components, respectively. The complex conjugate of U_Z is denoted by U_Z^*. The set of the coupling equations among the turbulence, ZF, and mean flow is derived. We investigate the mean flow generation in the case when the ZF is directly driven by turbulence. The finite amplitude ZF in the stationary state is obtained from the coupling equation.

The model of the plasma edge is proposed, and the boundary condition for the coupling equation is introduced. The zero frequency components can exist independent of the topology of the magnetic field. Actually, there is a flow with zero frequency in the scrape off layer (SOL) region, which is strongly prescribed by the particle and heat transport from the plasma. The zero frequency flow inside the plasma should be connected with that in the SOL. Namely, they are equal at the edge by exchanging their poloidal momentum. Therefore, the boundary condition for the zero frequency components can be written as

$$U_Z e^{iq_Z a} + U_Z^* e^{-iq_Z a} + U_{MF} = U_{SOL} \qquad (2),$$

where the position of the edge is represented by $x = a$, and U_{SOL} is the vorticity of the flow in the SOL. Here, for the first step, we set $U_{SOL} = 0$, for the simplicity. By using the boundary condition Eq. (2), the finite mean flow is expressed as

$$U_{MF} = -2|U_Z|\cos q_Z a \qquad (3).$$

The sign of the mean flow depends on the phase of the ZF at the edge.

The physical mechanism of mean flow generation is explained. The ZF is the wave in which the poloidal momentum is given and received between neighboring magnetic surfaces due to the deformation of the turbulence vorticity. When the ZF is not contiguous to the plasma edge, the net poloidal momentum is zero. On the other hand, when the ZF touches the edge, the exchange of the poloidal momentum across the plasma edge occurs, and the net momentum becomes finite. Therefore the mean flow is generated. The process is shown in Fig. 1. In the case of Fig. 1, the plasma receives the positive poloidal momentum from the SOL, and the positive mean flow is realized.

The poloidal velocity of the mean flow is evaluated as

$$\frac{V_{MF}}{V_d} \sim 2k_\theta L_{ZF} \left|\frac{U_{ZF}}{\omega_*}\right| \cos q_Z a \qquad (4),$$

where V_{MF}, V_d are the poloidal velocity of the mean flow and the diamagnetic drift velocity, respectively. The poloidal wavenumber of the turbulence is denoted by k_θ, L_{ZF} is the radial spatial scale length of the ZF, and ω_* is the frequency of the drift wave. In the case of $k_\theta L_{ZF} = 10, U_{ZF}/\omega_* = 0.1, \cos q_Z a = 1$, the estimated value of the mean flow is $V_{MF} = 2V_d$. The generated mean flow is comparable to the diamagnetic drift velocity, which is not negligible.

3. Summary and Discussion

The new mechanism of the mean flow generation is presented, investigating the system that consists of turbulence, and ZF with considering the plasma edge effect. Based on the fluid model, the set of coupling equations among turbulence, ZF, and mean flow is derived by evaluating the Reynolds stress with the wave-kinetic equation. The model of the plasma edge is proposed: the zero frequency components, ZF and mean flow, exchange the poloidal momentum with the flow in the SOL so that the value of the zero frequency components becomes equal to the flow in the SOL at the edge. The effect of the plasma edge is introduced in the coupling equations as the boundary condition. The finite mean flow is generated by the momentum exchange across the plasma edge, whose value is comparable to the diamagnetic drift velocity.

The geodesic acoustic modes (GAMs) are driven by turbulence when the safety factor becomes large. Even when the ZF can not get the energy from the turbulence directly, the finite ZF is driven by the nonlinear coupling of the GAMs [7] in the presence of inhomogeneous turbulence, as is near the edge. The finite mean flow is generated via the same process with the ZF.

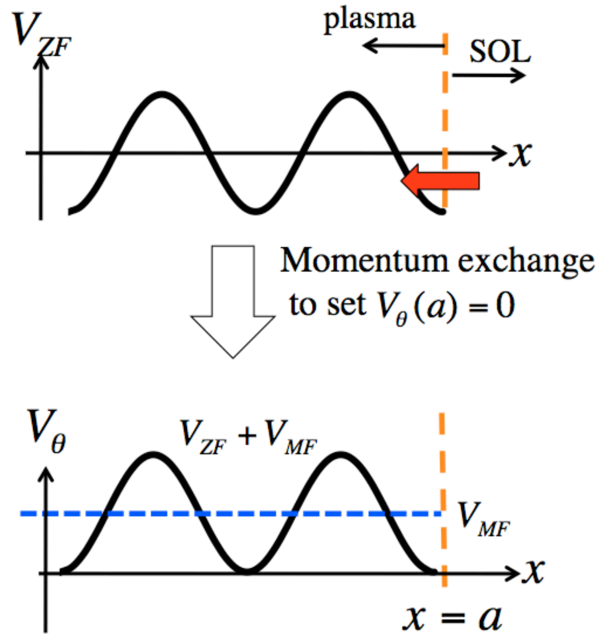

Fig. 1 Schematic of generation mechanism of the mean flow. The radial structure of the poloidal velocity with the zero frequency component, V_θ, is shown. The orange dot line shows the last closed flux surface. The red arrow in the upper figure shows the direction of the poloidal momentum transport.

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