§26. Magnetohydrodynamic Transport-Suppression Mechanisms due to Radial Electric Field and Poloidal Plasma Rotation in Tokamak's Reversed-Shear Confinement

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Tokamak's reversed-shear (RS) confinement modes of plasma are studied on the basis of the magnetohydrodynamic analysis of turbulent suppression. The mechanism of thermal-transport suppression in the modes is sought in two contexts. One is the combined effect of radial electric field and charge inhomogeneity. The similarity is pointed out between the internal transport barrier in RS modes and the edge counterpart in high-confinement modes is pointed out Another is the effect of poloidal plasma rotation. Its onset and sustainment processes are presented in light of a concave electric-current profile, and the relationship with the thermal-transport suppression is clarified.

Let us use the results about the MHD dynamo [1] and investigate the onset of poloidal flow. In the cylindrical coordinates (r, θ, z), we assume the axisymmetry of all statistical quantities and neglect the dependence on the toroidal direction. This simplification is done for illustrating a new mechanism of deriving the poloidal rotation, and it does not intend to lower the importance of toroidicity. Then those quantities depend on r and t only, and we may write $B=(0, B_\theta, B_z)$, $J=(0, J_\theta, J_z)$, $U=(0, U_\theta, U_z)$, which lead to $J\times B=(B_z J_\theta - B_\theta J_z, 0, 0)$. By employing the formula of turbulent Reynolds' stress, $\boldsymbol{R}=(R_{ij})$, the equation of motion is qritten as

$$\frac{\partial U}{\partial t}=-\left(-\frac{P_M}{\rho}+\frac{U_\theta^2}{r}-\frac{2}{3}K_R\right) +J\times B+\nu_T\Delta U-\nu_M\Delta B+\nu\Delta U \qquad (1)$$

In this equation, ν_T and ν_M are generated by turbulence. Attention is focused on the nonlinear interaction between plasma motion and magnetic fields leading to the generation of ν_T and ν_M.

The z component of the mean vorticity, Ω_z, that expresses a poloidal plasma flow, follows the relation

$$\frac{\partial \Omega_z}{\partial t}=\nu_T\Delta\Omega_z-\nu_M\Delta J_z\,. \qquad (2)$$

In the absence of the second ν_M-related term in Eq. (2), Ω_z is subject to the resistive effect only, and there is no room for its autonomous generation.

We now seek the Ω_z generation process due to the ν_M-related effect. We pick up its contribution and write

$$\frac{\partial \Omega_z}{\partial t}=-\frac{5\,C_\gamma}{7}\frac{K}{\varepsilon}W\Delta J_z+R_{\Omega 1}, \qquad (3)$$

where K, ε, and W are turbulent energy, dissipation and corss-helicity, respectively, and $R_{\Omega 1}$ denotes the remaining contribution. The generation rate of W, $\partial W/\partial t$, is given as

$$\frac{\partial W}{\partial t}=\beta J_z\Omega_z+R_W=C_\beta\frac{K^2}{\varepsilon}J_z\Omega_z+R_W. \qquad (4)$$

We eliminate W from Eqs.(3) and (4) and connect Ω_z directly with J_z. Here we focused attention on the temporal growth of W, and neglected the temporal change of J_z, K, and ε. Then we have

$$\frac{\partial^2\Omega_z}{\partial t^2}-\left(-\frac{5\,C_\beta\,C_\gamma}{7}\frac{K^3}{\varepsilon^2}J_z\Delta J_z\right)\Omega_z=R_{\Omega 2}, \qquad (5)$$

where $R_{\Omega 2}$ expresses all the remaining contributions. Equation (5) indicates that Ω_z may grow under the condition

$$\chi_\Omega{}^2\cong-\frac{5\,C_\beta\,C_\gamma}{7}\frac{K^3}{\varepsilon^2}J_z\Delta J_z>0, \qquad (6)$$

where χ_Ω represents its growth rate. The condition (6) is equivalent to

$$J_z\Delta J_z=J_zJ_z''+\frac{1}{r}J_zJ_z'<0. \qquad (7)$$

The first J_z''-related term in Eq. (7) is always positive near the maximum point. The second J_z' counterpart takes both signs, but it contributes to the onset of the growth just outside of the minimum-q_S point. From this situation, we may expect that the curvature of the electric-current profile in RS modes is essential for the generation of a poloidal flow.

In the study of improved confinement, the physics picture based on the role of electric field [2] is now extended to include the turbulent dynamo effect for the ERS mode. This model firstly provides an explanation for the strong poloidal rotation which ahs been observed in the ERS plasmas [3].

[1] Yoshizawa, A., *Hydrodynamic and Magnetohydrodynamic Turbulent Flows: Modelling and Statistical Theory* (Kluwer, Dordrecht, 1998).

[2] Itoh, K. and Itoh, S.-I., Plasma Phys. Controlled Fusion **38**, 1 (1996).

[3] Ida, K., Plasma Phys. Controlled Fusion **40**, 1429 (1998).