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Linear Analysis of Cross-field Dynamics with Feedback Instability on Detached Divertor Plasmas

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The theoretical model of the feedback instability is proposed to explain the mechanism of the correlation between the detachment and the cross-field plasma transport. It is shown that (1) the feedback instability on the detached divertor plasma can be induced in a certain condition in which the recombination frequency $\nu_{\rm rec}$ is larger than the ion cyclotron frequency $\Omega_{\rm ci}$ in the recombination region and the density gradient and the electric field in the direction perpendicular to the magnetic flux surface are not zero, and that (2) the feedback instability can provide the cross-field plasma transport in the boundary layer of magnetic fusion torus devices.

The correlation between the detachment and the cross-field plasma transport in the boundary layer has been reported in various magnetic confinement devices, that is, tokamak[1], helical[2], and linear[3] devices. Such a correlation is expected to expand the width of the heat flux to the divertor target, i.e., $\lambda_{\rm q}$. However, the physical dynamics of the correlation has not been revealed. In this study, we investigate the cross-field dynamics in the detached plasma state with the coupling model between magnetized plasmas characterized by different current mechanisms. In the recombination region in front of a divertor target, $\nu_{\rm rec}$ can be larger than $\Omega_{\rm ci}$ because of the high density and the low temperature. In such a situation, the cross-field motion of ions is mainly in the direction of the electric field, while that of electrons is almost in the direction of the $E \times B$ drift. Thus, the difference in the direction of motion may provide the cross-field current in the recombination region. On the other hand, the cross-field current can be generated by only the polarization, the grad-B, and the diamagnetic drifts in the upstream plasma. We have considered whether such a difference between the current mechanisms in each region induces the cross-field plasma transport.

In this study, we have derived the linear dispersion relation from the continuity equations,

$$\frac{\partial n^{\rm P}}{\partial t} + \nabla_\perp \cdot (n^{\rm P}\mathbf{v}^{\rm P}_{s\perp}) + \frac{\Gamma^{\rm P}_{s\parallel}(z=L_z) - \Gamma^{\rm B}_{s\parallel}}{L_z} = 0 \qquad (1)$$

and

$$\frac{\partial n^{\rm R}}{\partial t} + \nabla_\perp \cdot (n^{\rm R}\mathbf{v}^{\rm R}_{s\perp}) + \frac{\Gamma^{\rm B}_{s\parallel} - \Gamma^{\rm R}_{s\parallel}(z=-h)}{L_z} = -\alpha\left[(n^{\rm R})^2 - (n^{\rm R}_0)^2\right], \qquad (2)$$

and the charge conservation equations,

$$\nabla_\perp \cdot \mathbf{j}^{\rm P}_{s\perp} + \frac{j^{\rm P}_\parallel(z=L_z) - j^{\rm B}_\parallel}{L_z} = 0 \qquad (3)$$

and

$$\nabla_\perp \cdot \mathbf{j}^{\rm R}_{s\perp} + \frac{j^{\rm B}_\parallel - j^{\rm R}_\parallel(z=-h)}{L_z} = 0, \qquad (4)$$

in the upstream plasma and the recombination region in the simple configuration as shown in Fig. 1. In this configuration, the magnetic field is parallel to the z axis and the x and y directions correspond to the direction perpendicular to the magnetic flux surface and the toroidal direction in torus devices, respectively. Here, n is the plasma density, $\mathbf{v}_{s\perp}$ is the flow velocity perpendicular to the magnetic field, $\Gamma_{s\parallel}$ is the parallel flux, α is the recombination coefficient, n_0 is the plasma density at the equilibrium state, $\mathbf{j}_\perp$ and $\mathbf{j}_\parallel$ are the perpendicular and the parallel currents, the superscripts P, R, and B indicate the quantities in the upstream plasma, in the recombination region, and at the boundary between those regions, respectively, and the subscript s represents the particle species. The upstream plasma flow velocity $\mathbf{v}^{\rm P}_{s\perp}$ is composed of the $E \times B$, the polarization, the grad-B, and the diamagnetic drifts, while the recombination region flow velocity $\mathbf{v}^{\rm R}_{s\perp}$ includes each drift with the Hall mobility and the motion in the direction of the perpendicular electric field with the Pedersen mobility. Linearizing Eqs. (1)-(4), as a result, we obtain the cubic equation regarding the frequency ω as the dispersion relation. It is found that the one mode of them has a positive growth rate under a certain condition. Figure 2 shows the dependence of the growth rate γ of the unstable mode, i.e., the feedback instability mode, on the wave number k and the propagation direction θ. In Fig. 3 we present the dependence of the group velocity $v_{\rm g} = \partial\omega/\partial k$ of the unstable mode on k and θ. Here, the typical parameters for fusion torus devices are assumed as follows: $B = 5$ T, $\partial B/\partial x = -1$ T/m, $n^{\rm P}_0 = 5 \times 10^{19}$ m^{-3}, $\partial n^{\rm P}_0/\partial x = -1.67 \times 10^{21}$ m^{-4}, the initial electric fields $E^{\rm P}_{x0} = E^{\rm R}_{x0} = -100$ V/m, the electron and ion temperatures $T^{\rm P}_{\rm e} = T^{\rm P}_{\rm i} = 50$ eV, $T^{\rm R}_{\rm e} = T^{\rm R}_{\rm i} = 0.3$ eV, $\nu_{\rm rec}/\Omega_{\rm ci} = 10$, $L_z = 10$ m, $h = 0.3$ m, the ion-to-electron mass ratio $m_{\rm i}/m_{\rm e} = 3.67 \times 10^3$, and the ion-to-electron charge ratio $q_{\rm i}/|q_{\rm e}| = 1$. In those figures, the area inside the red curve designates the unstable region in which the feedback instability can be induced. Thus, Figs. 2 and 3 indicate that the waves $k\rho^{\rm P}_{\rm s} > 0.8$ and $\theta \sim 3\pi/4$ can transport the plasma lump with the speed $\sim 0.002\ c^{\rm P}_{\rm s}$. The simple estimation shows that the maximum of heat flux density is reduced to $1 - (v_{{\rm g}x}/c^{\rm R}_{\rm s})(\tilde{n}/n^{\rm R}_0)(h/\lambda^{\rm B}_{\rm q}) \approx 82\%$ of the initial value and that the heat flux width is expanded to $1 + (h/\lambda^{\rm B}_{\rm q})(v_{{\rm g}x}/c^{\rm R}_{\rm s}) \approx 280\%$ of the initial width if $\tilde{n}/n_0^{\mathrm{R}} \sim 0.1$ and $\lambda_{\mathrm{q}}^{\mathrm{B}} \sim 3$ mm. Here, $v_{\mathrm{g}x}$ is the x component of v_{g} and $\tilde{n}$ is the time averaged density of the transported plasma lump.

Furthermore, to verify the feedback instability model, the spiraling plasma ejection observed around the recombination front under the detached divertor condition in the NAGDIS-II linear device experiment[3] is analyzed, in which the NAGDIS-II contributes to the establishments of the detachment and the cross-field transport mechanisms for future fusion reactors such as ITER and DEMO. The radial speed $v_r \sim 80$ m/s at $r \sim 20$ mm and azimuthal speed $v_\theta \sim 200$ m/s at $r \sim 5$ mm obtained in the experiment are in good agreement with $v_{\mathrm{g}x} \sim 800$ m/s and $v_{\mathrm{g}y} \sim 200$ m/s estimated by the theoretical model with the NAGDIS-II parameters if v_r is reduced as r increases.

[1]Potzel S *et al.* 2013 *J. Nucl. Mater.* **438** S285.
[2]Tanaka H. *et al.* 2010 *Phys. Plasmas* **17** 102509.
[3]Tanaka H. *et al.* 2018 *Plasma Phys. Control. Fusion* **60** 075013.

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