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Kinetic analysis of recycling plasma in an oblique magnetic field

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Abstract

A high-recycling divertor plasma is treated using a kinetic model to examine magnetic field effects on plasma flow. A plasma equation, which describes electrostatic potential structures in a recycling plasma, is derived in an integro-differential form similar to Poisson's equation. The potential drop in the presheath has a dependence on magnetic field parameters even if the scale length of the magnetic presheath is much smaller than the decay length of neutral density. As a result of formation of the magnetic presheath, secondary-electron emission coefficient is limited to a value much smaller than unity.

Keywords: Divertor plasma; Magnetic sheath; Plasma-neutral process; Secondary electron; Space-charge limitation

1. Introduction

Correct understanding of magnetic field effects on the potential formation is necessary to research the particle and heat transport of a plasma in an edge confinement region, in the scrape-off layer, or in a divertor chamber of tokamaks. In the magnetic field intersecting equipotential surfaces at a shallow angle, formation mechanisms of the potential are provided by the Lorentz force [1]. Several papers about the magnetic presheath have been presented recently, in which characteristics of the presheath and potential structures were investigated in detail [2,3].

Limited research efforts, however, have been conducted in investigating the magnetic field effects on the potential formation in high-recycling plasmas [4]. Surface plasma structures of recycling plasma were calculated by using kinetic treatment of the transport equation [5–7]. Solutions were found with a peak and with a steep gradient in the potential near the plate. Magnetic field effects are predicted to become effective for such a plasma having a steep gradient at the boundary. These papers, however, did not treat plasma structures owing to magnetic field effects. On the other hand, the magnetic presheath results in a smaller Debye sheath, and the limitation of secondary-electron emission as discussed by Hobbs and Wesson [9] is related to the magnitude of the Debye sheath. Then, formation of the magnetic presheath between a plasma and target plates is expected to reduce the limited secondary-emission coefficient to a value much smaller than unity.

In this paper, we first formulate the plasma equation of a recycling plasma on the base of a kinetic treatment. The plasma equation is numerically solved to study effects of oblique magnetic field on potential structures. Next, we examine space-charge limitation of secondary-electron influx in magnetic field with the shallow angle of incidence. Limitation of the emission coefficient to a value much smaller than unity is shown by the calculation using the sheath equation.

2. Kinetic model and plasma equation

2.1. Formulation of the plasma equation

We consider a plasma flowing along a uniform magnetic field with shallow angle of incidence and

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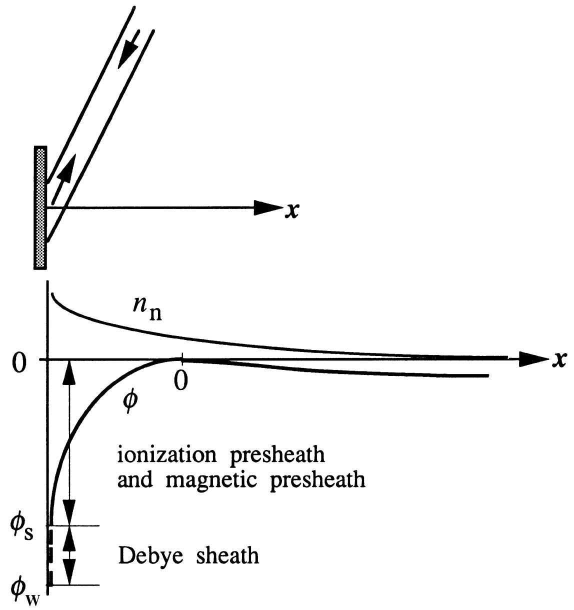

Fig. 1. Sketch of the problem region in an oblique magnetic field with cold-plasma recycling.

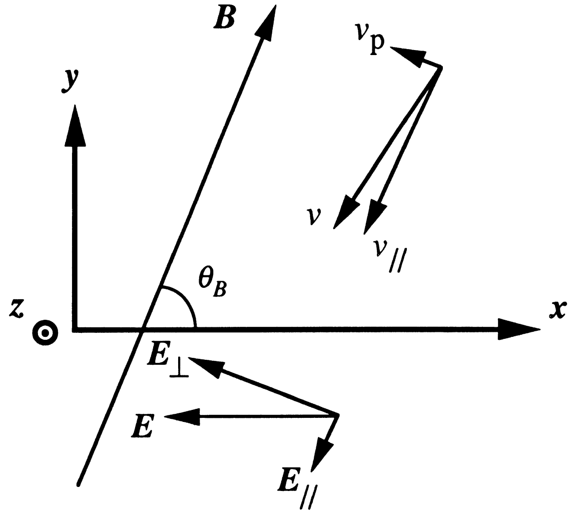

Fig. 2. Geometry of the model considered.

striking a plate where it is neutralized. The neutrals emitted from the plate reenter the plasma and are reionized. Electron density is assumed to obey the Boltzmann relation, and distribution function of hot ions coming from tokamak SOL is taken as a half-Maxwellian with temperature T_h. Coulomb collisions in the neutral recycling region are neglected on the assumption of $\lambda_c \gg \lambda_i$, λ_{cx},λ_n for a high-temperature plasma with T $\geqslant$ 25 eV, where λ_c, λ_i and λ_{cx} are the mean free paths for Coulomb scattering, ionization and charge exchange, and λ_n is the decay length of neutral density. When the neutral reflux becomes large, a single maximum of the potential is formed in the recycling region as illustrated in Fig. 1 [5].

Under the collisionless limit, one can derived the plasma equation on the base of a kinetic analysis using the drift approximation for ion orbit. The geometry of the model considered in the present analysis is shown in Fig. 2. An ion moving with the velocity. v_x in the x direction feels variation of the perpendicular electric field with time. Since the ion polarization-drift velocity is

$$v_p \equiv \frac{dE_\perp/dt}{\omega_{ci}B} = -\frac{v_x}{\omega_{ci}B}\sin\,\theta_B\frac{d^2\phi}{dx^2}, \tag{1}$$

the resultant drift velocity in the x direction is expressed by

$$v_x = v_\parallel\cos\theta_B\left(1+\frac{\sin^2\theta_B d^2\phi}{\omega_{ci}B dx^2}\right)^{-1}. \tag{2}$$

If initial velocity of incoming ion is expressed by (u_x, u_y, u_z), Jacobian $\partial(u_x, u_y, u_z)/\partial(v_x, v_y, v_z) = v_x/u_x$ is obtained from constants of motion $\varepsilon = 1/2Mv^2 + e\phi(x)$, $p_y/M \equiv v_y + \omega_{ci}x\sin\theta_B$, and $p_z/M \equiv v_z - \omega_{ci}y\cos\theta_B$. After averaging over the ion gyromotion, particle density of incoming hot ions is expressed in the form

$$\begin{aligned} n_h(x) &= \left(1+\frac{\sin^2\theta_B}{\omega_{ci}B}\frac{d^2\phi}{dx^2}\right)\int\frac{u_\parallel}{v_\parallel}f_h(\boldsymbol{u})d\boldsymbol{u} \\ &= \left(1+\frac{\sin^2\theta_B}{\omega_{ci}B}\frac{d^2\phi}{dx^2}\right)n'_h(x). \end{aligned} \tag{3}$$

The ion density has a dependence on x due to the polarization drift.

The kinetic equation of cold ions produced in the recycling region is simply described by

$$\begin{aligned} &\sigma v_x(x,\varepsilon,\mu)\frac{\partial f_c(x,\varepsilon,\mu,\sigma)}{\partial x} \\ &\quad = S_c(x,\varepsilon,\mu) - v(x,\varepsilon,\mu)\frac{f_c(x,\varepsilon,\mu,\sigma)}{\lambda_{cx}(x)}, \end{aligned} \tag{4}$$

using the energy $\varepsilon = 1/2Mv^2 + e\phi$, the magnetic moment $\mu = 1/2Mv_\perp^2/B$ and the direction of the motion $\sigma = \pm 1$ [8]. The neutral density profile is modeled by $n_n(x) = n_n\exp(x/\lambda_n)$, and the mean free paths λ_i and λ_{cx} are assumed to be in inverse proportion to n_n. Multiple charge-exchange events are considered, but a hot component of neutrals is neglected. The particle source of cold ions produced by ionization or by charge exchange is given by

$$\begin{aligned} S_c(\varepsilon,\mu,x) &= \frac{\Gamma_0}{\lambda_i}\left(1+\frac{\lambda_i}{\lambda_{cx}}+\frac{y}{\lambda_{cx}}\right) \\ &\quad\times\frac{M^2}{4\pi(kT_c)^2}v_\parallel\exp[-(\varepsilon-e\phi)/kT_c],\quad x\leqslant 0 \end{aligned} \tag{5a}$$

$$= \frac{\Gamma_0}{\lambda_i}\left(1+\frac{\lambda_i}{\lambda_{cx}}(2\ \exp(y/\lambda_{cx})-1)-\frac{y}{\lambda_{cx}}\right) \times \frac{M^2}{4\pi(kT_c)^2} v_{\parallel} \exp\left[-(\varepsilon - e\phi)/kT_c\right], \quad x \geqslant 0 \tag{5b}$$

where $y = \lambda_n(1-\exp(-x/\lambda_n))$, and $x=0$ is a point of the potential maximum, Γ_0 is the particle flux of escaping hot ions at $x=0$. Distribution function of cold ions is obtained by integrating the kinetic equation along the trajectory after averaging over the gyromotion. Particle density of cold ions is expressed in the integral form with respect to x, ε and μ.

$$n_c(x) = \left(1+\frac{\sin^2\theta_B}{\omega_{ci}B}\frac{d^2\phi}{dx^2}\right)\frac{2\pi B}{M^2}\sum_\sigma \int d\varepsilon \int \frac{d\mu}{v_{\parallel}(x,\varepsilon,\mu)} \times \int \frac{dx'}{\cos\theta_B}\frac{S_c(x',\varepsilon,\mu)}{v_{\parallel}(x',\varepsilon,\mu)} g(x,x') = \left(1+\frac{\sin^2\theta_B}{\omega_{ci}B}\frac{d^2\phi}{dx^2}\right) n'_c(x), \tag{6}$$

where $g(x,x')$ expresses reduction of f_c due to charge-exchange collisions. Integration over the ε-μ space can be performed in the similar manner as described in Ref. [8].

The integro-differential equation for the potential ϕ so-called plasma equation is obtained from the quasi-neutrality condition $n_h + n_c = n_e$ in the similar form to Poisson's equation

$$\left(\frac{C_s \sin\theta_B}{\omega_{ci}}\right)^2 \frac{e}{kT_e}\frac{d^2\phi}{dx^2} = n_0 \exp\left(\frac{e\phi}{kT_e}\right) \times \left(n'_h + n'_c\right)^{-1} - 1, \tag{7}$$

where $C_s \equiv (kT_e/M)^{1/2}$ is the ion sound speed. It is seen from Eq. (7) that the scale length for potential variation is of the order of $C_s \sin\theta_B/\omega_{ci}$.

2.2. Numerical results of presheath potential

For the purpose of showing magnetic field effects on the potential formation, we solve the plasma equation. Eq. (7) can be solved numerically by transforming it into a set of finite difference equations. The maximum value of ϕ defined to be zero, and the potential at the sheath edge is determined so that the ion distribution satisfies the generalized Bohm condition with equality at the sheath edge. We first solve Eq. (7) for various ratios of the length $\rho_s \equiv C_s/\omega_{ci}$ to the decay length of the neutrals λ_n, neglecting charge-exchange collisions. Reflux ratios of the particle are assumed to be 1 both at the potential maximum and at the surface material. Steep gradient of the electrostatic potential is formed near the boundary as shown in Fig. 3(a). Effects of charge exchange are evaluated by solving Eq. (7) for $\lambda_i = 1.3\lambda_{cx}$. A large potential drop, which is proportional to the value of λ_n/λ_{cx}, is formed in the recycling region as shown in Fig. 3(b) to overcome friction caused by charge-exchange collisions. Dependence of the potential drop on the magnetic field strength is shown in Fig. 4. The total potential drop in the plasma decreases with increasing ρ_s/λ_n even if the scale length ρ_s is much smaller than the decay length of neutrals λ_n. Velocity of the polarization drift across magnetic field increases as the potential gradient becomes steep. This is a reason why the potential drop decreases with increasing of ρ_s/λ_n. Decrement of the potential drop in the presheath remarkably affects secondary-electron emission coefficient under the space-charge limitation as mentioned in the next section.

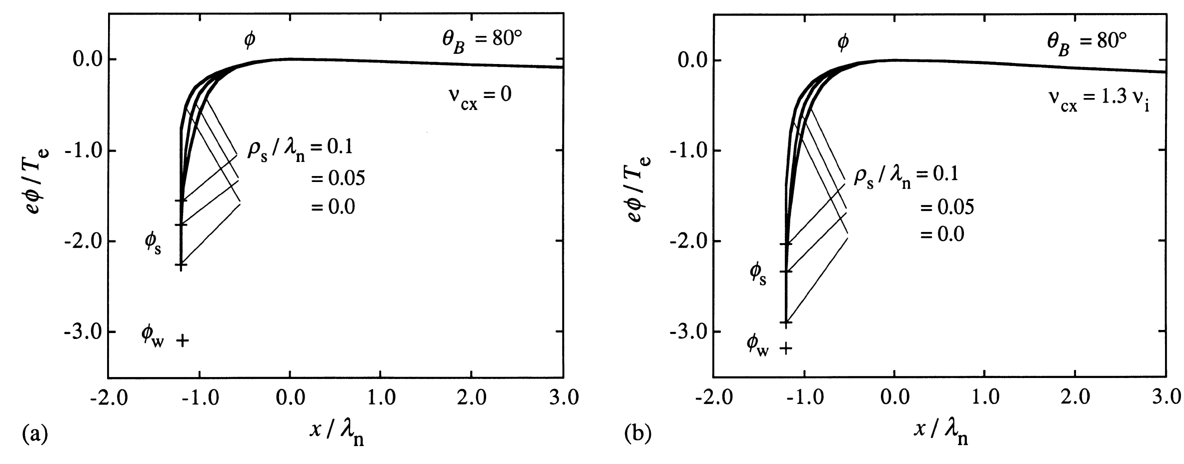

Fig. 3. Spatial profiles of the electrostatic potential for various ratios of the length $\rho_s \equiv C_s/\omega_{ci}$ to the decay length of the neutrals λ_n for a recycling plasma (a) without charge exchange and (b) with charge exchange. Here, reflux ratios of the particle are assumed to be 1 both at the potential maximum and at the surface material.

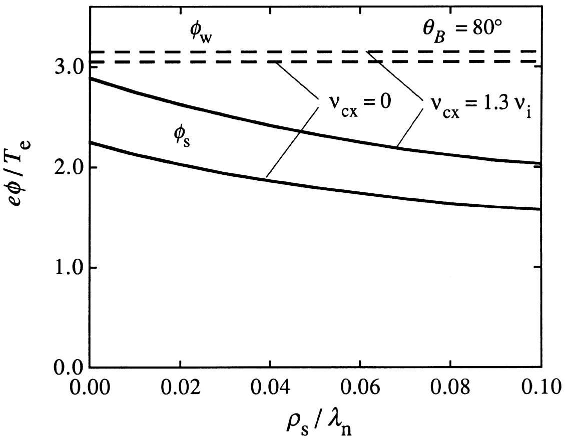

Fig. 4. Potential ϕ_s at the sheath edge as a function of the scale length ρ_s.

Since the electron distribution function is assumed to be Maxwellian in the present calculation, potential drop at the presheath $|\phi_s|$ becomes larger than the total potential drop $|\phi_w|$ when the magnetic angle approaches 90°. For large magnetic angles which many tokamaks can have, one need to treat electron dynamics using a kinetic model in investigating potential structures of the transition layer. The electron distribution function will be modified from a Maxwellian for magnetic angles in this range. As a result of the modification, the potential drop at the presheath will be more or less smaller than that obtained from the present calculation.

3. Space-charge limitation of secondary-electron inflow

The magnetic presheath results in a smaller Debye sheath and the potential drop at the sheath decreases as the magnetic angle increases. Then, we can expect the space–charge limitation of the emission coefficient, which is related to the potential drop at the sheath, to a small value when the magnetic angle is close to 90°. To simplify the analysis, we neglect plasma-neutral interactions in the present section. Ions are assumed to be cold and to arrive at the entrance of the magnetic presheath with velocity C_s along magnetic field lines. The magnetic presheath is formed due to polarization drift of the ions, and the potential drop at the magnetic presheath $|\phi_s|$ is determined from the plasma equation. In the presence of electron emission, the sheath equation for a plasma with parameters $\rho_s \gg \lambda_D \gg \rho_{se}$ is

$$\begin{aligned}
\frac{1}{2}\left(\frac{e\lambda_D}{kT_e}\right)^2\left(\frac{d\phi}{dx}\right)^2 &= \frac{Mv_{xs}^2}{kT_e}\left[\left(1-\frac{2e(\phi-\phi_s)}{Mv_{xs}^2}\right)^{\frac{1}{2}}-1\right] \\
&- \left[1-\frac{\gamma}{1-\gamma}\left(\frac{Mv_{xs}^2}{2e(\phi_s-\phi_w)}\right)^{\frac{1}{2}}\frac{1}{\cos\theta_B}\right] \\
&\times\left[1-\exp\left(\frac{e(\phi-\phi_s)}{kT_e}\right)\right] \\
&- \frac{2\gamma}{1-\gamma}\left(\frac{Mv_{xs}^2}{2kT_e}\right)^{\frac{1}{2}}\left(\frac{e(\phi_s-\phi_w)}{kT_e}\right)^{\frac{1}{2}} \\
&\times\left[1-\left(\frac{\phi-\phi_w}{\phi_s-\phi_w}\right)^{\frac{1}{2}}\right]\frac{1}{\cos\theta_B},
\end{aligned} \tag{8}$$

where the initial kinetic energy of the secondary electrons is neglected. The potential drop at the sheath $\phi_s - \phi_w$, the ion flow velocity at the sheath edge v_{xs}, and emission coefficient γ under conditions of the space-charge limitation are obtained from simultaneous equations, $J_i = J_e, \partial(n_i - n_e)/\partial\phi = 0$ at $\phi = \phi_s$ [9], and $d\phi/dx = 0$ at $\phi = \phi_w$. Fig. 5(a) and (b) shows results under the conditions of space-charge limitation. The limited emission coefficient decreases from the critical value $\gamma_c \simeq 0.8$ to a value much smaller than 1 as the magnetic angle increases from 0° to 90°. The change of the magnetic presheath potential due to the secondary-electron emission is negligibly small. Formation of the

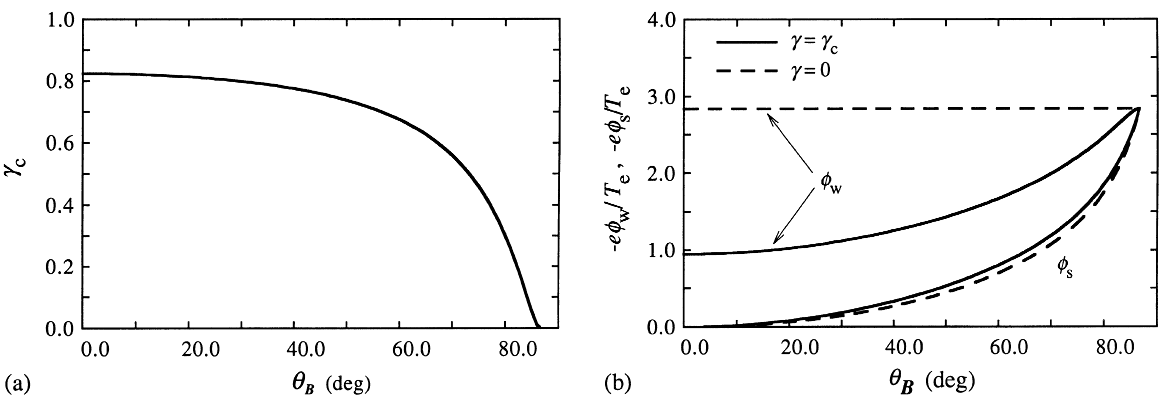

Fig. 5. (a) Electron emission coefficient γ_c. (b) Potentials at the sheath edge and at the wall, ϕ_s and ϕ_w, as a function of magnetic angle θ_B under the conditions of space-charge limitation. Broken lines are results for $\gamma = 0$.

magnetic presheath results in effective suppression of the secondary-electron inflow.

4. Conclusions

A high-recycling divertor plasma is treated using a kinetic model to examine magnetic field effects on plasma flow. Plasma equation, which describes electrostatic potential structures of a recycling plasma in magnetic field with shallow angle of incidence, is derived in an integro-differential form similar to Poisson's equation. The potential drop in the presheath has a dependence on magnetic field parameters even if the scale length of the magnetic presheath is much smaller than the decay length of neutral density. An oblique magnetic field has dramatic effects of preventing secondary electrons from flowing through the Debye sheath into the divertor plasma. The electron emission coefficient is limited to a value much smaller than 1 by the space-charge effect in the Debye sheath, which is enhanced due to formation of the magnetic presheath.

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