

STRUCTURES OF ELECTROSTATIC POTENTIAL IN A TRANSITION LAYER ACROSS MAGNETIC FIELD LINES

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Abstract

A plasma equation describing electrostatic potential structures across magnetic field lines is derived in an integro-differential form similar to Poisson's equation. Solution of the plasma equation exhibits various potential structures across magnetic field lines: sheath-like, soliton-like, shock-wave-like, or double-layer-like structures. Potential drop in the recycling region near walls has a remarkable dependence on magnetic-field parameters even if ion Larmor radius is much smaller than the neutral decay length.

1. Introduction

When the magnetic field intersects equipotential surfaces at a shallow angle, the magnetic field is predicted to have considerable effects on potential formation through the Lorentz force. Since the potential structure across magnetic field lines is closely connected with plasma transport, correct understanding of formation mechanisms of the electrostatic potential is necessary to research the particle and heat transport of a plasma in an edge confinement region and in a divertor chamber of tokamaks, or to study behavior of a plasma in the ionosphere.

Using a numerical model, Chodura showed using a numerical model that the transition layer between a plasma and target plates in the divertor chamber has a double structure composed of the magnetic presheath and the Debye sheath [1]. His papers, however, do not give any clear physical picture on the formation of the magnetic presheath. Although several papers about the magnetic presheath have been presented recently [2,3], characteristics of nonlinear electrostatic phenomena and potential structures were not investigated in detail.

Purposes of this paper are to formulate a plasma equation for electrostatic potential across magnetic field lines considering plasma-neutral interactions, to characterize nonlinear electrostatic phenomena due to ion polarization drift, and to study effects of oblique magnetic field on the plasma structure near walls .

2. Kinetic Model and Plasma Equation

We consider a plasma flowing along a uniform magnetic field. Electron density is assumed to obey the Boltzmann relation. Coulomb collisions in the particle source region are neglected on the assumption of $\lambda_c \gg \lambda_i, \lambda_{cx}$, where λ_c , λ_i and λ_{cx} are the mean free paths for Coulomb scattering, ionization and charge exchange collisions. 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. 1. An ion moving with the velocity component v_x feels variation of the perpendicular electric field with time. Since the ion polarization-drift velocity is

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

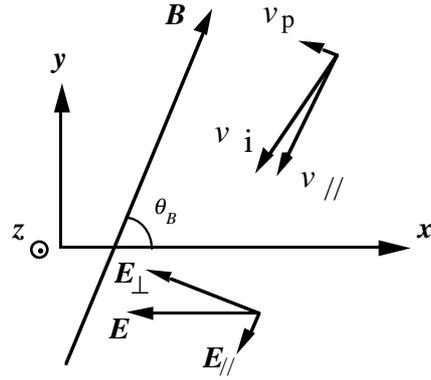


Fig. 1. Geometry of the mode considered.

the resultant drift velocity in the x direction is expressed by

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

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

$$n_h(x) = \left(1 + \frac{\sin^2\theta_B}{\omega_{ci}B} \frac{d^2\phi}{dx^2} \right) \int \frac{u_{//}}{v_{//}} f_h(\mathbf{u}) d\mathbf{u}. \quad (3)$$

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

The kinetic equation of cold ions produced in the particle-source region is simply described by

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

using the energy $\varepsilon = 1/2Mv^2 + e\phi$, the magnetic moment $\mu = 1/2Mv_{\perp}^2 / B$ and the direction of the motion $\sigma = \pm 1$ [4]. 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 of the distribution function with respect to x , ε and μ . Integration of f_c over the ε - μ space can be performed in the similar manner as described in Ref. [4]. The integro-differential equation for the potential ϕ so called plasma equation is obtained from the quasineutrality condition $n_h + n_c = n_e$ in the similar form to Poisson's equation :

$$\left(\frac{C_s \sin \theta_B}{\omega_{ci}}\right)^2 \frac{e}{kT_e} \frac{d^2 \phi}{dx^2} = n_0 \exp\left(\frac{e\phi}{kT_e}\right) \times (n'_h + n'_c)^{-1} - 1, \quad (5)$$

where $C_s \equiv (kT_e/M)^{1/2}$ is the ion sound speed. It is seen from Eq. (5) that the scale length for potential variation is of the order of $C_s \sin \theta_B / \omega_{ci}$.

3. Numerical Results of Plasma Equation

We first study solutions of the plasma equation neglecting plasma-neutral interactions. Potential profile of the magnetic presheath calculated from Eq. (5) is shown in Fig. 2. The potential at the sheath edge, i.e., $x = 0$, is determined so that the Bohm criterion for the stable sheath formation can be satisfied with equality. The potential drop at the magnetic presheath becomes large as the magnetic angle increases, and the width of the presheath is several times as large as the characteristic length C_s / ω_{ci} .

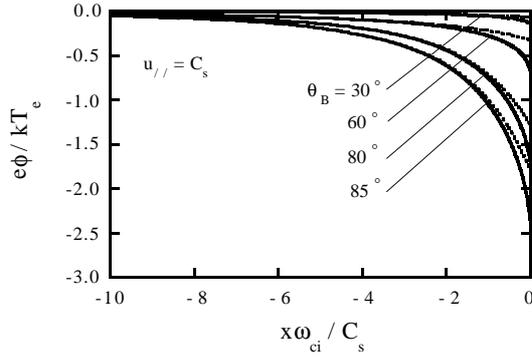


Fig. 2. Potential profile $\phi(x)$ of the magnetic presheath in a plasma.

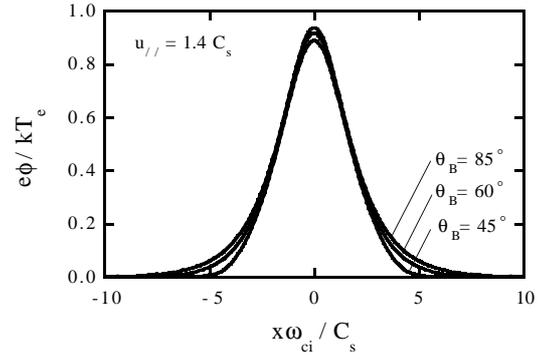


Fig. 3. Potential profile of soliton.

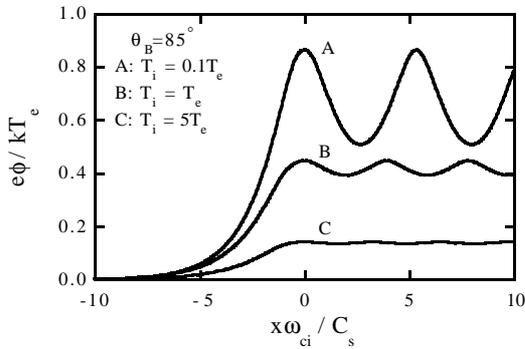


Fig. 4 Shock-wave-like structure of the potential f .

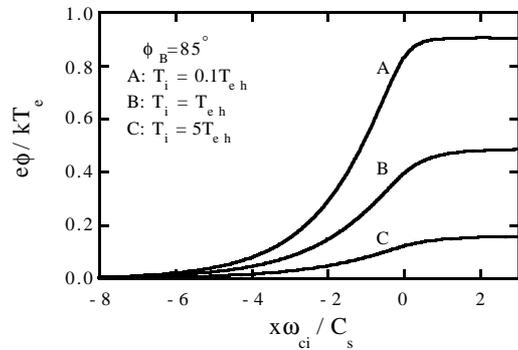


Fig. 5. Double-layer-like structure of the potential.

If the parallel ion speed at $\phi = 0$ exceeds the sound speed, we can obtain soliton-like potential structure as shown in Fig. 3. Potential profile has a weak dependence of the magnetic angle, and the spatial variation of the potential is characterized by C_s / ω_{ci} . BGK-like modes are also found from the plasma equation (5) if ions have a spread in parallel velocity, which exhibit various potential structures such as shock-wave-like and double-layer-like structures as shown in Figs. 4 and 5.

For the purpose of showing effects of the magnetic field and of plasma-neutral interactions on the potential structure in the recycling region near divertor targets [5,6], we solve the plasma equation under the boundary condition at the sheath edge. Formation of the presheath potential is due to ion polarization-drift and due to production of cold ions. A maximum in the presheath potential is produced for large reflux of neutrals, and steep gradient of the electrostatic potential is formed near the boundary. Effects of charge exchange are evaluated by solving Eq. (5) for $v_{cx} = 1.3v_i$. A large potential drop, which is proportional to the value of λ_n / λ_{cx} , is formed in the recycling region to overcome friction caused by charge-exchange collisions. 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 .

4. Conclusion

Kinetic analysis is carried out to investigate stationary potential structures across magnetic field lines. Plasma equation, which describes electrostatic potential across magnetic field lines, is derived in an integro-differential form similar to Poisson's equation. Solution of the plasma equation exhibits various potential structures across magnetic field lines: sheath-like, soliton-like, periodic-wave, shock-wave-like, or double-layer-like structures. The potential drop in the recycling region near target plates has a remarkable dependence on magnetic field parameters even if ion Larmor radius is much smaller than the neutral decay length.

Subjects for a future study are effects of plasma-neutral interactions and of magnetic-field configurations on nonlinear electrostatic phenomena.

References

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