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Electrostatic potential in a collisionless plasma flow along open magnetic field lines

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ABSTRACT

Formation of the steady-state potential in a collisionless plasma flow along nonuniform magnetic field lines terminated at a wall is studied theoretically under the condition that a particle source in a plasma can be neglected. It is found that the plasma flow is required to satisfy the generalized Bohm criterion over the whole region for the formation of the steady-state continuous potential in the divergent magnetic field. A monotonically falling potential can build up from the inside of the magnetic throat to the wall only if the Bohm criterion is marginally satisfied at the throat. Numerical solutions to Poisson's equation show that a potential profile outside the throat is strongly dependent upon the particle density of electrons trapped between the throat and the wall. Controllability of the potential by increasing the trapped-electron density is discussed briefly.

Keywords ; open magnetic field, collisionless plasma, electrostatic potential, magnetic throat, generalized Bohm criterion, trapped electron

I. INTRODUCTION

Potential formation in a plasma flowing to a wall in the presence of a nonuniform magnetic field is an important problem in various fusion devices as well as in plasma processing techniques. Knowledge of the electrostatic potential profile in a collisionless plasma is necessary to understand phenomena in the end region of mirror machines or in the edge layer of field-reversed configurations[1]. Moreover, knowledge of the potential variation is the key to knowing parameters of a plasma for design of a direct energy convertor and evaluation of its efficiency[2-4]. This problem is also interest in connection with high temperature divertor plasma operation of a toroidal magnetic fusion system aiming at confinement improvement and reduction of the heat load on a plate[5].

The control of the potential profile has been a main subject of a tandem mirror in relation to plasma confinement and thermal transport to the end walls[6]. Although there have been several models which consider the axial potential profile in the confinement region of mirror systems in order to evaluate the thermal barrier depth[7] and the height of the plug potential[8], there have been few attempts to examine the potential formed in the region near the outer mirror throat or in the end region. Recently, a plasma flow along a nonuniform magnetic field to a wall was treated with kinetic analyses[9-11]. Their analyses provide an important basis for the study of potential formation in a plasma mainly produced by recycling of the neutral gas, such as a plasma in the divertor chamber of a toroidal system. We, however, know of few attempts to verify characteristics of the potential formed in a plasma escaping through a nonuniform magnetic field in which there is no particle source.

In this paper, we theoretically investigate potential formation in a collisionless plasma flow to a wall in the presence of nonuniform magnetic field. A particle source is assumed to be negligibly small in the open region. We derive necessary conditions to be satisfy for formation of a monotonically falling potential in the open region or in the inner region near the magnetic throat. Moreover, we numerically solve Poisson's equation for model distribution functions to examine the potential formation along magnetic field lines. We also consider the effect of trapped electrons on the presheath potential and briefly discuss the controllability of the potential by the combination of a spatially varying magnetic field and the electron cyclotron heating.

The outline of the paper is as follows. A general description of the presheath potential is obtained from quasi-neutrality in Sec. II. Model distribution functions of ions and electrons are picked out to obtain the expression of the plasma-sheath equation in Sec. III. Results of numerical calculations are presented and discussed in Sec. IV. The conclusions are summarized in sec. V

II. FORMATION OF A MONOTONICALLY FALLING POTENTIAL

We consider a simple profile of magnetic field strength as sketched in Fig.1. A plasma coming out through the magnetic throat at $x = 0$ is neutralized at the wall located at $x = L$, which is perfectly absorbing and electrically floating. The ion motion is assumed to be collisionless on the scale length of the magnetic field variation. We also neglect a particle source outside the throat, assuming the particle density of a plasma produced in this region much smaller than the one of the plasma flowing through the throat.

The distribution functions of the ions and electrons satisfy the Vlasov equation. Thus we can generally express the steady-state distribution function as a function of constants of motion on the assumption of no particle source. The energy of a particle,

$$\varepsilon = \frac{1}{2} m_j (v_\perp^2 + v_\parallel^2) + q_j \phi(x) \quad , \tag{1}$$

is a constant of motion, where m_j is the mass, q_j is the charge, $v_\perp$ and $v_\parallel$ are the perpendicular and parallel components of velocity. The electrostatic potential formed in the plasma, $\phi(x)$, is defined to be zero at $x = 0$. The magnetic moment,

$$\mu = \frac{1}{2} m_j v_\perp^2 R(x)/B_0 \quad , \tag{2}$$

is taken as a constant of motion, like ε, where the mirror ratio $R(x)$ is the ratio of the magnetic field strength B_0 at $x = 0$ to the local value $B(x)$ at axial co-ordinate x. The subscript 0 denotes the value at $x = 0$ throughout this paper. The particle density n_j of species j is obtained as a function of R and ϕ by integrating the distribution function $f_j(\varepsilon, \mu)$ over the velocity space.

The electrostatic potential is determined, in general, from Poisson's equation

$$\nabla^2 \phi = e \Big[n_e\big(\phi(x), R(x)\big) - Z n_i\big(\phi(x), R(x)\big) \Big] / \varepsilon_0 \quad , \tag{3}$$

where Z is the charge number of ions. One can see that, so long as the characteristic scale length, L_c, for potential variation is large compared to the Debye length λ_D, the solution for $\phi(x)$ obtained from Eq.(3) is well approximated by the one obtained from the quasi-neutral approximation $Zn_i = n_e$. The two solutions differ by $O(\lambda_D^2/L_c^2)$ and the solution to Eq.(3) satisfy charge-neutrality to the same order.

Differentiating $Zn_i = n_e$ with respect to x, we obtain the differential equation

$$\frac{d\phi}{dx} = -\frac{\partial(Zn_i - n_e)/\partial R}{\partial(Zn_i - n_e)/\partial\phi}\frac{dR}{dx} \tag{4}$$

from which we can determine the potential $\phi(x)$ all over the region except the sheath region if there is no singular point. In the presence of an expanding magnetic field, ions coming out through the magnetic throat are accelerated towards the wall and their density drops accordingly. Electrons in the open region consist of electrons passing through the magnetic throat, most of which is reflected by the potential ϕ, and electrons trapped between the throat and the wall by a well of the effective potential $\mu B_0/R - e\phi$.The trapped-electron density becomes large with increasing the mirror ratio R, while the reflected-electron density drops inversely as the mirror ratio increases as same manner as the escaping-ion density. Since the value of $\partial(Zn_i - n_e)/\partial R$ depends on a ratio of trapped- to reflected-electron density, the trapped electrons have considerable effects upon the potential formation in the plasma. The derivative $\partial(Zn_i - n_e)/\partial R$ is negative in the whole range of R for all but very small trapped-electron densities. In this case, we obtain a monotonically falling solution $\phi(x)$ to Eq.(4) continuing from $x = 0$ to $x = L$, if the derivative $\partial(Zn_i - n_e)/\partial\phi$ is negative throughout the open region. This solution satisfies a necessary condition for the formation of the sheath potential just in front of the wall, which is expressed by $\partial(Zn_i - n_e)/\partial\phi \leq 0$. The derivative $\partial(Zn_i - n_e)/\partial R$ can have a positive value for much small trapped-particle densities, and then a monotonically falling solution is obtained if the derivative $\partial(Zn_i - n_e)/\partial\phi$ is positive for $x > 0$. We, however, can exclude such a solution because it does not satisfy the necessary condition for the sheath formation. The derivative $\partial(Zn_i - n_e)/\partial\phi$ is negative, in general, for $x > 0$ once it has a negative value at the throat because of rapid decrease of the electron density with decrease of the potential.

The inequality $\partial(Zn_i - n_e)/\partial\phi \leq 0$ gives the restriction to the ion distribution function. This is rewritten by using the ion distribution function in the form[12]

$$\frac{Ze}{M}\int_0^\infty dv_\parallel \frac{f_i(v_\parallel)}{v_\parallel^2} \leq \frac{\partial n_e}{\partial\phi} \ , \qquad (5)$$

which becomes the same form as the generalized Bohm criterion presented by Harrison et al.[13] when the electron distribution function is a Maxwellian distribution with temperature T_e. The ion distribution function f_i must be zero at $v_\parallel = 0$ to have a finite value of the integral in the expression (5). On the other hand, the ion distribution function in the interior of the throat is expected to be continuous at the separatrix which divides the trapped from the passing region of velocity space provided trapped ions exist inside the throat. These facts mean that the passing ions must be accelerated in the inside region close to the throat before their arrival at $x = 0$ so as to satisfy the criterion (5).

We can consider the inner region near the throat where the trapped-ion density is smaller than the passing-ion density, if the criterion (5) is satisfied at $x = 0$ and the ion distribution function is continuous at the separatrix in the interior. The electron distribution function in this region can be expected to approach a Maxwellian distribution because of relaxation inside the throat. Since the derivative $\partial(Zn_i - n_e)/\partial R$ has a finite negative value for such a plasma, the sign of $\partial(Zn_i - n_e)/\partial\phi$ must be opposite to the one of dR/dx for a monotonically varying potential near the throat. Then it must change from positive to negative at $x = 0$ as x increases. Consequently, it is found that a monotonically decreasing potential, which is necessary to accelerate ions, can build up in the vicinity of the throat only if the criterion (5) is fulfilled with equality at $x = 0$.

When we calculate the potential in the inner region of the magnetic throat such as the plug cell of a tandem mirror system, we must consider trapped ions the distribution function of which is finite and continuous at the separatrix in velocity space. In the inner region at a distance from the throat, where the trapped-ion density is much larger than the passing-ion density, in general, the derivative $\partial(Zn_i - n_e)/\partial\phi$ is negative and the derivative $\partial(Zn_i - n_e)/\partial R$ is positive. On the contrary, $\partial(Zn_i - n_e)/\partial\phi$ is positive and $\partial(Zn_i - n_e)/\partial R$ is negative just in front of the throat as mentioned above. One can see from this fact that there must be a saddle point, at which $Zn_i - n_e = 0$, $\partial(Zn_i - n_e)/\partial\phi = 0$ and $\partial(Zn_i - n_e)/\partial R = 0$ hold true simultaneously, in the intermediate region where the trapped-ion density becomes comparable with the passing-ion density, if a monotonically varying potential builds up over the entire region including the inner region. Distribution functions of the plasma will be very restricted owing to the existence of such a saddle point. Whether such a continuously varying potential in a steady state can build up throughout the system or not is an open problem. It is difficult to determine the spatial distribution of ϕ over the entire region because one must solve the Vlasov-Poisson equation self-consistently, determining the separatrix in velocity space under the consideration of ion motion in a nonuniform magnetic field.

III. MODEL DISTRIBUTION FUNCTIONS

We need to express the distribution function of electrons and ions in order to calculate the axial potential profile between the magnetic throat and the wall and the one in the vicinity of the throat. The ion drift speed must be supersonic at the throat so as to satisfy the generalized Bohm criterion. Thus we choose a cut-off Maxwellian distribution with the cut-off energy ε_c given by

$$f_i(\varepsilon,\mu) = \frac{2n_0/Z}{\mathrm{erfc}\left[(\varepsilon_c/kT_i)^{1/2}\right]}\left(\frac{m_i}{2\pi kT_i}\right)^{3/2}\exp\left(-\frac{\varepsilon}{kT_i}\right)h(\varepsilon-\mu B_0-\varepsilon_c) \qquad (6)$$

as a model ion distribution function. Here $\mathrm{erfc}(y)$ is the complementary error function and $h(y)$ is the Heaviside unit function defined by

$$h(y) = \begin{cases} 1 & , y \geq 0 \\ 0 & , y < 0 \end{cases} \quad .$$

Level surfaces of this model distribution function in $v_\parallel - v_\perp$ space at $R = 2$ and $-e\phi/kT_e = 1$ are shown in Fig. 2(a).

Electrons are classified into three groups, that is, passing electrons which can reach the wall, electrons reflected by the decelerating potential, and electrons trapped between the throat and the wall by a well of the effective potential $\mu B(x) - e\phi(x)$. Since reflected electrons are subject to relaxation inside the magnetic throat, we assume their distribution function to be Maxwellian. The trapped-electron phase space is filled in by scattering of the reflected electrons due to collisions in velocity space. Thus the distribution function must be continuous at the separatrix which divides the trapped from the reflected region of velocity space. We pick a model distribution function for the electrons in the form

$$f_e(\varepsilon,\mu)=n_0\left(\frac{m_e}{2\pi kT_e}\right)^{3/2}\exp\left(-\frac{\varepsilon}{kT_e}\right)g\left(\frac{\varepsilon-\mu B_0}{kT_e}\right), \tag{7}$$

where the function $g(y)$ is defined by

$$g(y)=\begin{cases}1 & , \; y\geq 0\\ \exp(\alpha y) & , \; y<0\end{cases} \quad .$$

The parameter α describes the degree to which the trapped-ion distribution function is reduced : $\alpha=0$ corresponds to Maxwellian trapped electrons ; and increasing α from 0 to ∞ describes successively smaller numbers of trapped electrons. Level surfaces of the model electron distribution function at $R=2$ and $-e\phi/kT_e=1$ are shown in Fig.2(b).

The particle density of species j is obtained as functions of R and ϕ by integrating f_j over the velocity space. The resulting expression of the ion density is

$$n_i(\phi,R)=\frac{n_0/Z}{\exp\left(\frac{\varepsilon_c}{kT_i}\right)\operatorname{erfc}\left[\left(\frac{\varepsilon_c}{kT_i}\right)^{1/2}\right]}\left\{\exp\left(\frac{\varepsilon_c-Ze\phi}{kT_i}\right)\operatorname{erfc}\left[\left(\frac{\varepsilon_c-Ze\phi}{kT_i}\right)^{1/2}\right]\right.$$

$$\left.-\left(\frac{R-1}{R}\right)^{1/2}\exp\left(\frac{R}{R-1}\frac{\varepsilon_c-Ze\phi}{kT_i}\right)\operatorname{erfc}\left[\left(\frac{R}{R-1}\frac{\varepsilon_c-Ze\phi}{kT_i}\right)^{1/2}\right]\right\}, \tag{8}$$

and that of the electron density is

$$n_e(\phi,R)=n_0\left[\exp\left(\frac{e\phi}{kT_e}\right)-\frac{\alpha(R-1)}{1+\alpha(R-1)}\left(\frac{R-1}{R}\right)^{1/2}\exp\left(\frac{R}{R-1}\frac{e\phi}{kT_e}\right)\right]. \tag{9}$$

These expressions are continuous and differentiable with respect to R and ϕ.

The ion flux per magnetic flux tube with unit cross section at the throat is given by

$$\Gamma_i = \frac{n_0}{Z}\left(\frac{2kT_i}{\pi m_i}\right)^{1/2}\left\{\exp\left(\frac{\varepsilon_c}{kT_i}\right)\operatorname{erfc}\left[\left(\frac{\varepsilon_c}{kT_i}\right)^{1/2}\right]\right\}^{-1}. \quad (10)$$

The electron flux is similarly given by

$$\Gamma_e = \frac{n_0}{2}\left(\frac{2kT_e}{\pi m_e}\right)^{1/2}\left[R_L\exp\left(\frac{e\phi_w}{kT_e}\right) - \frac{\alpha(R_L-1)^2}{1+\alpha(R_L-1)}\exp\left(\frac{R_L}{R_L-1}\frac{e\phi_w}{kT_e}\right)\right], \quad (11)$$

where R_L is the mirror ratio at $x = L$. The wall potential ϕ_w in Eq. (11), which is one of two boundary conditions to solve Poisson's equation, is uniquely determined by imposing the umbipolarity of the fluxes, $Z\Gamma_i = \Gamma_e$.

IV. NUMERICAL RESULTS AND DISCUSSION

The inequalities $\partial(Zn_i - n_e)/\partial R \leq 0$ and $\partial(Zn_i - n_e)/\partial\phi \leq 0$ must be satisfied throughout the exterior of the magnetic throat, $x \geq 0$, as described in Sec.II in order to obtain a monotonically decreasing continuous potential. These inequalities restrict a range of parameters of the model distribution functions given by Eqs.(6) and (7). Figures 3(a) and 3(b) show domains in $\alpha - \varepsilon_c$ space for any point in which we can obtain a solution of Eq.(4) continuous from $x = 0$ to $x = L$. The cut-off energy of ions, ε_c, has a lower limit resulting from $\partial(Zn_i - n_e)/\partial\phi = 0$. This means that ions must have a supersonic drift speed to avoid the discontinuity of the potential. The cut-off energy also has a upper limit resulting from $\partial(Zn_i - n_e)/\partial R = 0$ if the parameter α has a value larger than a certain value. The range of ε_c becomes smaller as α becomes larger, that is, as the trapped-electron density decreases. Such tendency is remarkable when the ratio of ion to electron temperatures is small.

Although the assumption of quasi-neutrality provides a good approximation for a smoothly varying potential in the plasma, one must numerically solve Poisson's equation to determine a potential profile over the entire region from the throat to the wall. If we approximate the problem as one-dimensional then we replace $\nabla^2\phi$ by $d^2\phi/dx^2$, and an appropriate set of boundary conditions consists of values of ϕ at the boundaries. The value of ϕ at the throat is defined to be zero and the one at the wall is determined from $Z\Gamma_i = \Gamma_e$. Poisson's equation can be solved numerically by transforming it into a set of finite difference equations. We use a solution of Eq.(4) to guess an initial set of ϕ, and ensure sufficient resolution near the wall by introducing a nonuniform grid.

Figure 4 shows the numerically calculated potential for the model field $R(x) = 1 + (R_L - 1)(x/L)^2$ with $R_L = 10$, where the hydrogen plasma with $T_i/T_e = 1$ and $\lambda_{D0}/L = 0.005$ is assumed. The cut-off energy of the model ion distribution function is chosen as $\varepsilon_c/kT_e = 0.187$ so as to satisfy the generalized Bohm criterion marginally at the throat. In this case, the gradient of the potential has a finite value at $x = 0$ nevertheless the gradient of $R(x)$ is zero at the throat. The solid curves A, B and C in Fig.4 show solutions for successively smaller ratios of the trapped- to the total-electron numbers. The sheath potential with the width several times as large as the Debye length is formed just in front of the wall. The density profiles of trapped electrons, reflected electrons, and passing ions for a Maxwellian electron distribution ($\alpha = 0$) are shown in Fig.5. We see that the trapped electrons remarkably affect the potential profile and the presheath potential drop. For much small trapped-electron densities, a descent of the presheath potential is localized near the magnetic throat, and then the presheath potential approaches asymptotically to a constant value as the mirror ratio increases. For large trapped-electron densities, the presheath has a gradually varying potential profile and the potential drop increases with increasing of the mirror ratio. The increase of the presheath potential drop due to the existence of trapped electrons leads to the decrease of the sheath potential.

In order to satisfy the generalized Bohm criterion at $x = 0$, ions coming out through the magnetic throat must have a supersonic drift speed and their distribution function must be zero at $v_{\|} = 0$. This fact implies the existence of the monotonically falling potential to accelerate ions in the inner region near the throat. Figure 6 show the potential profiles in the vicinity of the throat obtained from the quasi-neutrality approximation for various values of the cut-off energy ε_c. We ignored ions trapped inside the throat, assuming that their density, which vanishes at $x = 0$, is much smaller than the passing-ion density in the region near the throat. The results confirm the fact described in Sec.II, that is, a monotonical potential profile can be obtained only if the generalized Bohm criterion is fulfilled with equality at the throat. For cut-off energies smaller than the critical value $\varepsilon_c/kT_e = 0.187$, one cannot obtain a continuous potential. On the contrary, for cut-off energies larger than the critical value, one can find a continuous potential profile, but it is not monotonical as indicated in Fig.6.

The contribution of trapped electrons to the increase of the presheath potential drop suggests the possibility of effective potential control in the open region by increasing the trapped-electron density through ECRH (electron cyclotron resonance heating) or ionization of neutral gas in the region near the wall. Since the ECRH increases the electron energy perpendicular to the magnetic field, electrons passing through the mirror throat can be kicked in the trapped region of velocity space by the rf field, and they are trapped until scattering out from the trapped region. In the open region with a large mirror ratio, such as the end region of a tandem mirror, almost all electrons produced by ionization near the wall are trapped in a well of the effective potential $\mu B - e\phi$. Hence, the ionization will contribute to the increase of the presheath potential drop provided the cooling effect of ionization is not so large. The large potential barrier at the presheath inhibits the inflow of high-Z impurity ions from the wall towards the confined plasma. Moreover, it will prevent a remarkable increase of convective electron heat loss caused by secondary electron emission from the wall. It is well known that secondary electron emission has a negligibly small influence on the presheath potential under the condition of a fixed electron temperature, while it remarkably reduces the sheath potential[14,15]. Thus, one can expect that the large presheath potential acts as a thermal insulator in place of the sheath potential when a large number of electrons are trapped in the open region of a system such as a tandem mirror, even if the sheath potential is reduced to a small value due to secondary electron emission. The ECRH power necessary to maintain the trapped-electron density is expected to be small compared with the convective electron heat outflow if the collision frequency is much smaller than the one inside the throat. A precise calculation considering the power balance of a plasma are necessary to make sure of the possibility of potential control.

V. CONCLUSIONS

We have studied formation of the steady-state electrostatic potential in a collisionless plasma flowing out through the magnetic throat to a wall under the condition that a particle source in a plasma can be ignored. We have expressed Poisson's equation for a theoretical model to examine potential formation along magnetic field lines from an inside point near the magnetic throat to the wall. It is found that satisfaction of the generalized Bohm criterion is required to avoid the discontinuity of the potential just beyond the magnetic throat, and then ions passing through the throat must be accelerated before they arrive at the throat. A monotonically falling potential to accelerate the passing ions can be formed in the inner region near the throat only if the generalized Bohm criterion is marginally satisfied at the throat.

Numerical solutions to Poisson's equation show that trapped electrons in the open region affect on the potential formation remarkably. For very small trapped-electron densities, the presheath potential drop is localized near the throat and the presheath potential approaches asymptotically to a constant value as the magnetic field strength decreases along magnetic field lines. For large trapped-particle densities, the presheath potential drop continuously increases with decreasing the magnetic field strength along field lines. These results suggest the possibility of effective potential control in the open region by the combination of an expanding magnetic field and the ECRH heating.

Our results obtained from the analysis and the numerical calculation present one of the bases of the total understanding of the potential formation in the open region of a mirror system or in the edge layer of a field reversed configuration. The present results may also be applicable to a low density and high temperature plasma in a modified expanding bundle divertor aiming at improving the energy confinement and reducing the heat load on the wall[5].

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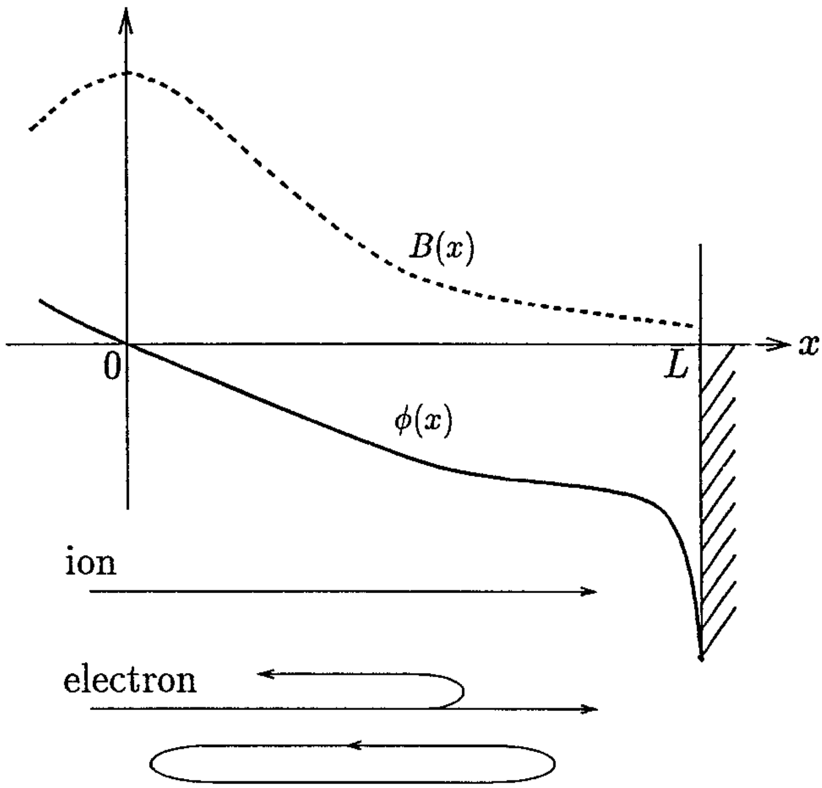

Fig. 1 Schematic diagram of the manetic field profile (dotted line) and the electrostatic potential profile (solid line) in the open region. Typical paths of particles are schematically shown in the region between the mirror throat and the floating wall.

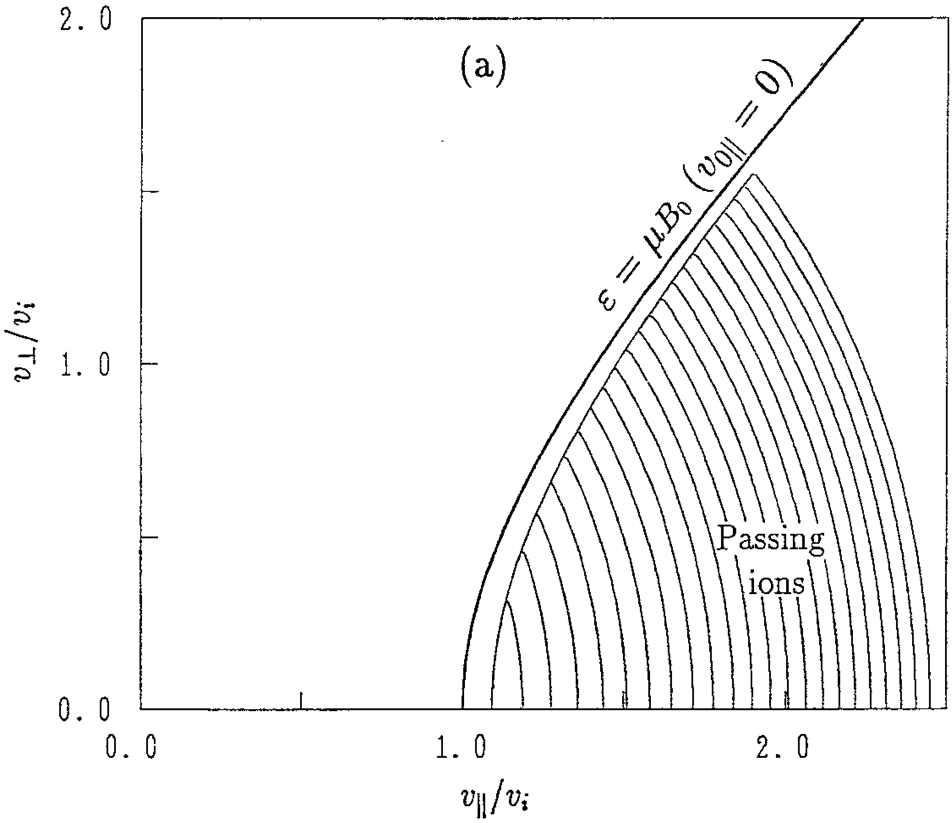

Fig. 2(a) Level surfaces at $R = 2$ and $e\phi/kT_e = -1.0$ for the model ion distribution function given by Eq.(6) with $\varepsilon_c/kT_e = 0.187$. Ratio of f on adjacent contours is 0.79.

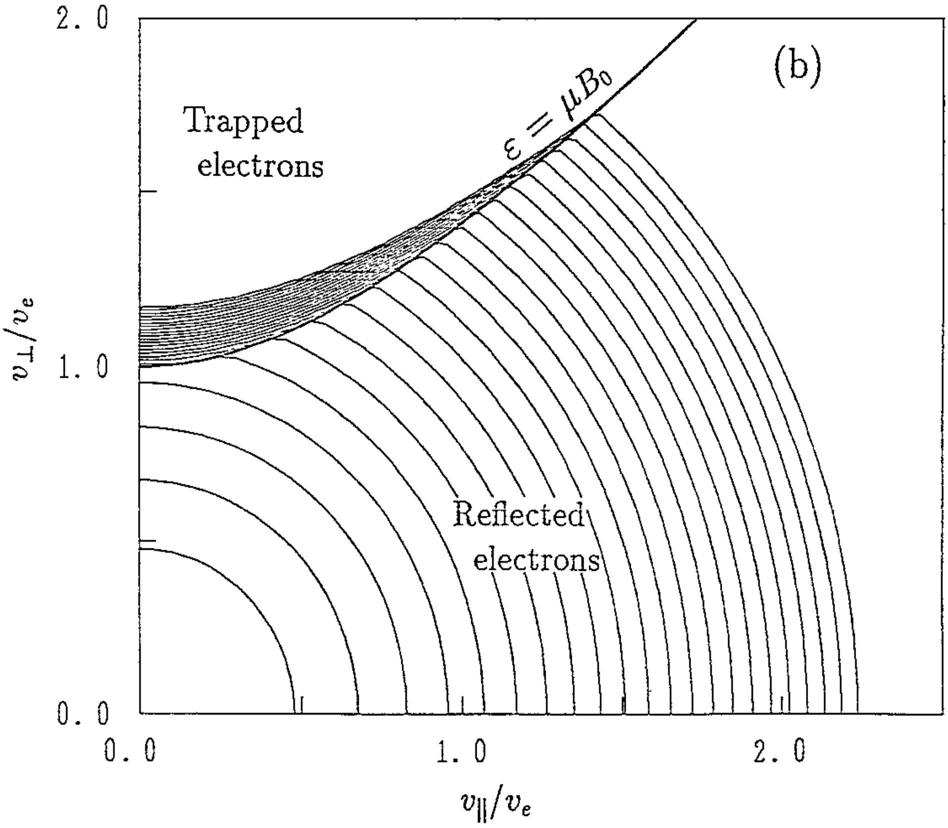

Fig. 2(b) Level surfaces at $R = 2$ and $e\phi/kT_e = -1.0$ for the model electron distribution function given by Eq.(7) with $\alpha = 10$. Ratio of f on adjacent contours is 0.79.

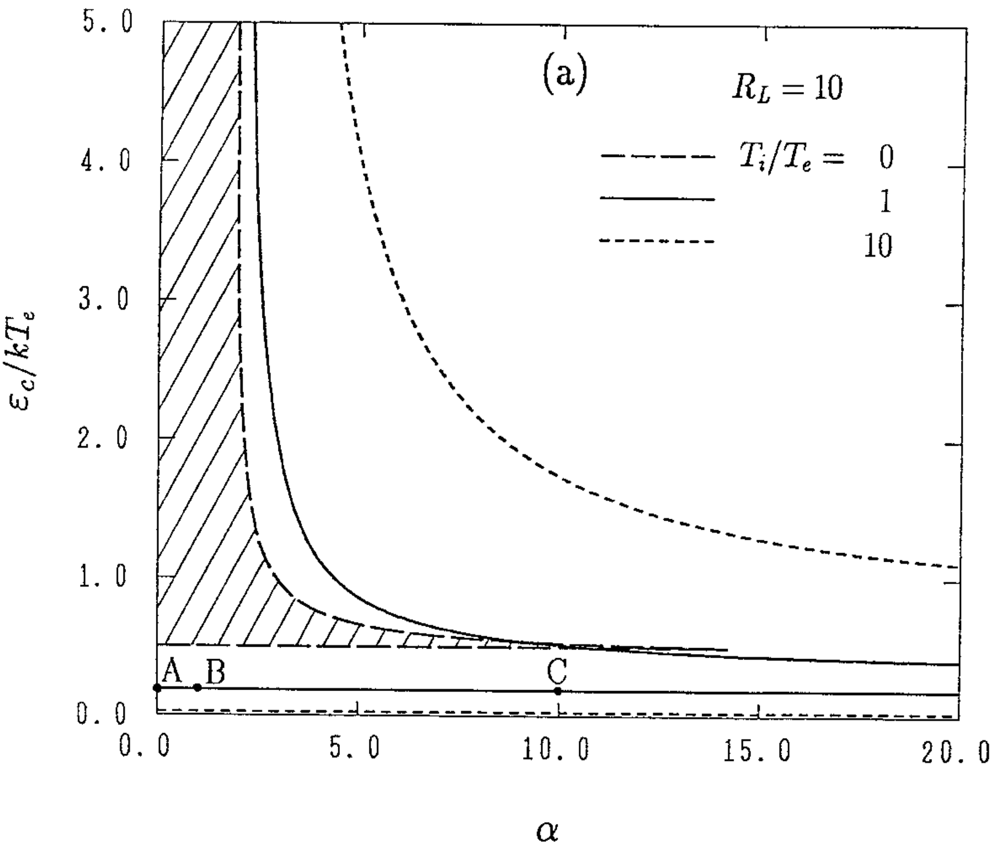

Fig. 3(a) Domain in $\alpha - \varepsilon_c$ space where monotonically varing continuous potential can be formed in the plasma for various ion temperatures. Here α is the reducing parameter of the model electron distribution function given by Eq.(7) and ε_c is the cut-off potential of the model ion distribution function given by Eq.(6).

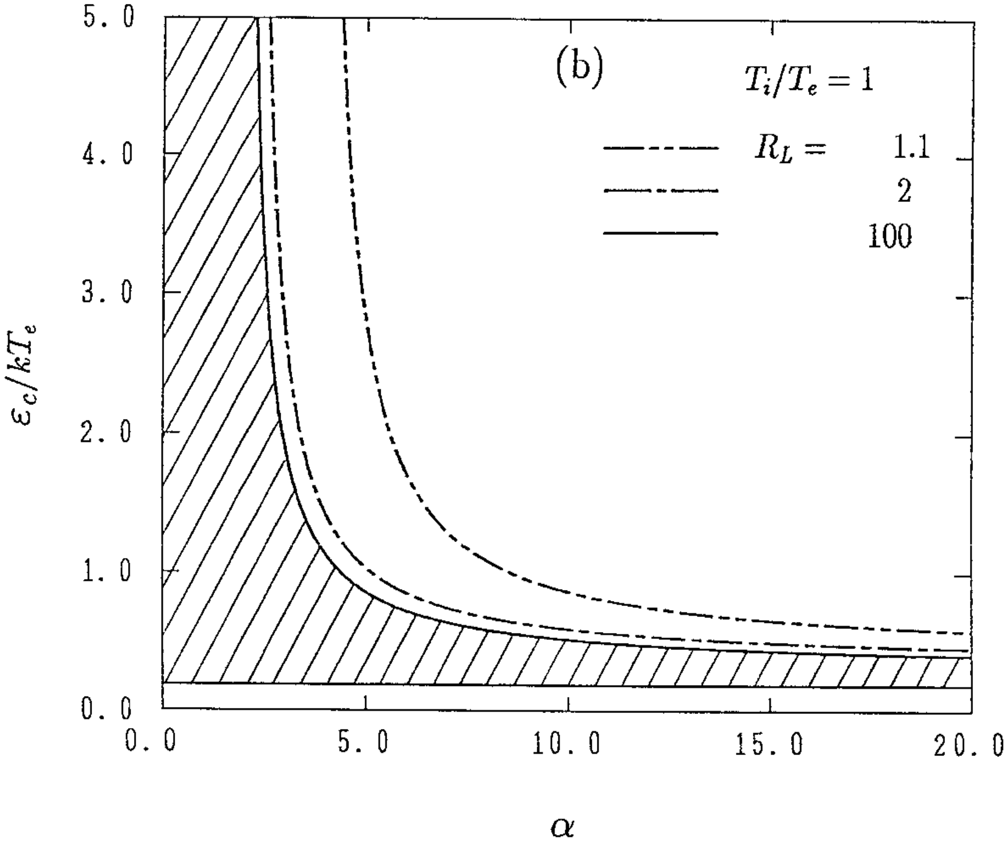

Fig. 3(b) Domain in $\alpha - \varepsilon_c$ space where monotonically varing continuous potential can be formed in the plasma for various mirror ratios at the wall.

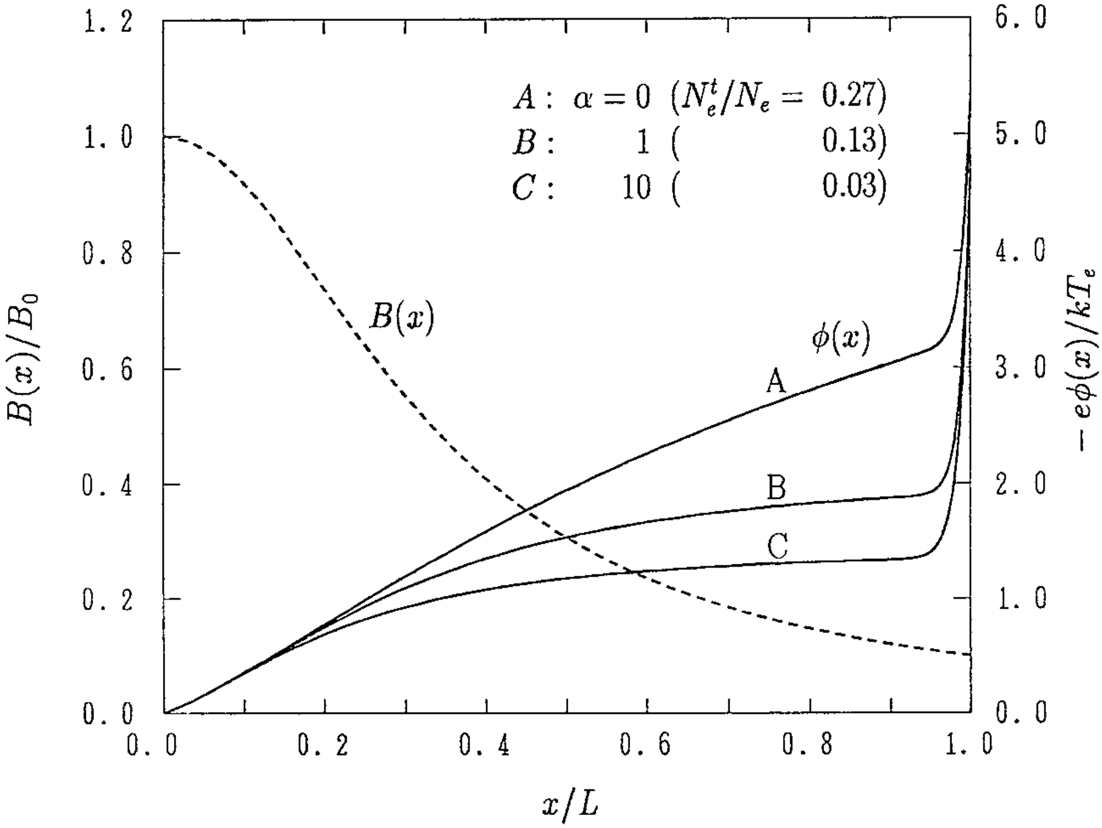

Fig. 4 Potential profile $\phi(x)$ in the model field $B_0/B(x) = 1 + (R_L - 1)(x/L)^2$ with $R_L = 10$ for various values of the parameter α of the model electron distribution function. Curves A, B and C represent results for parameters pointed in Fig.3(a). Parameters of the model distribution functions are $\varepsilon_c/kT_e = 0.187$ and $T_i/T_e = 1$. The values of α and the corresponding ratios of trapped- to total-electron numbers are : (A) $\alpha = 0$, $N_e^t/N_e = 0.27$; (B) $\alpha = 1$, $N_e^t/N_e = 0.13$; (C) $\alpha = 10$, $N_e^t/N_e = 0.03$.

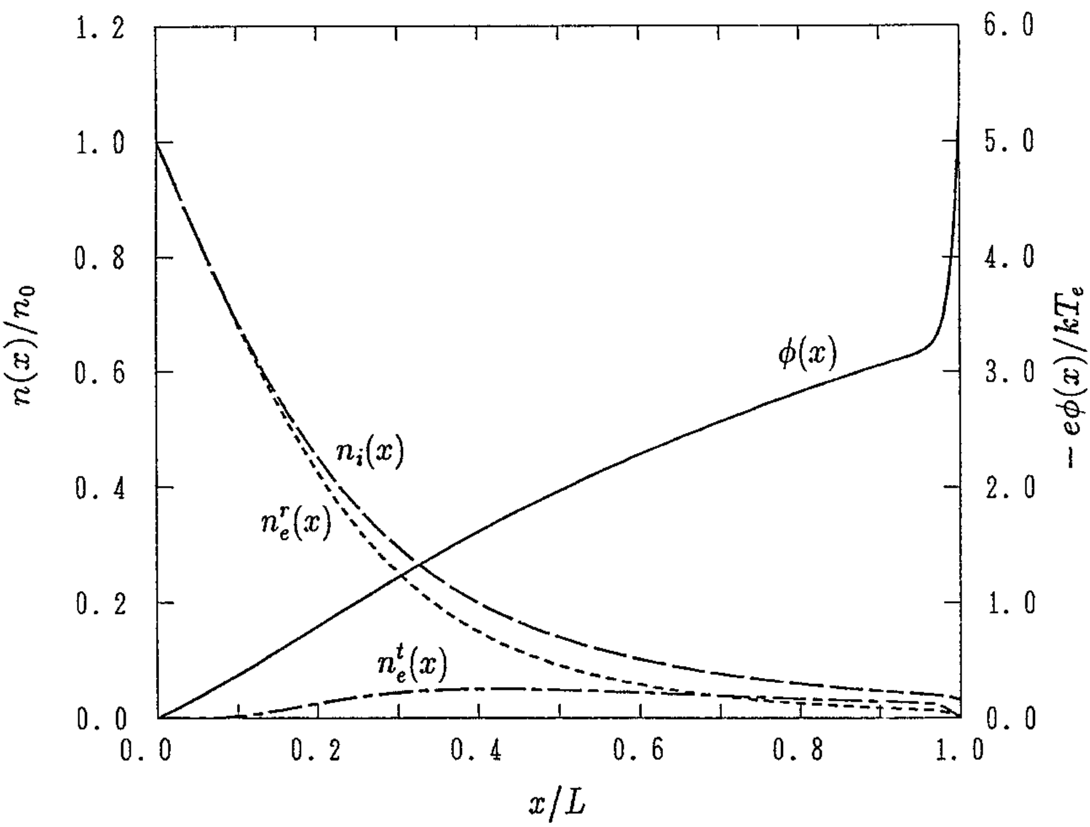

Fig. 5 Density profile of ions $n_i(x)$, reflected electrons $n_e^r(x)$ and trapped elecrons $n_e^t(x)$, and potential profile $\phi(x)$ for the model distribution functions with $\varepsilon_c/kT_e = 0.187, T_i/T_e = 1$and $\alpha = 0$.

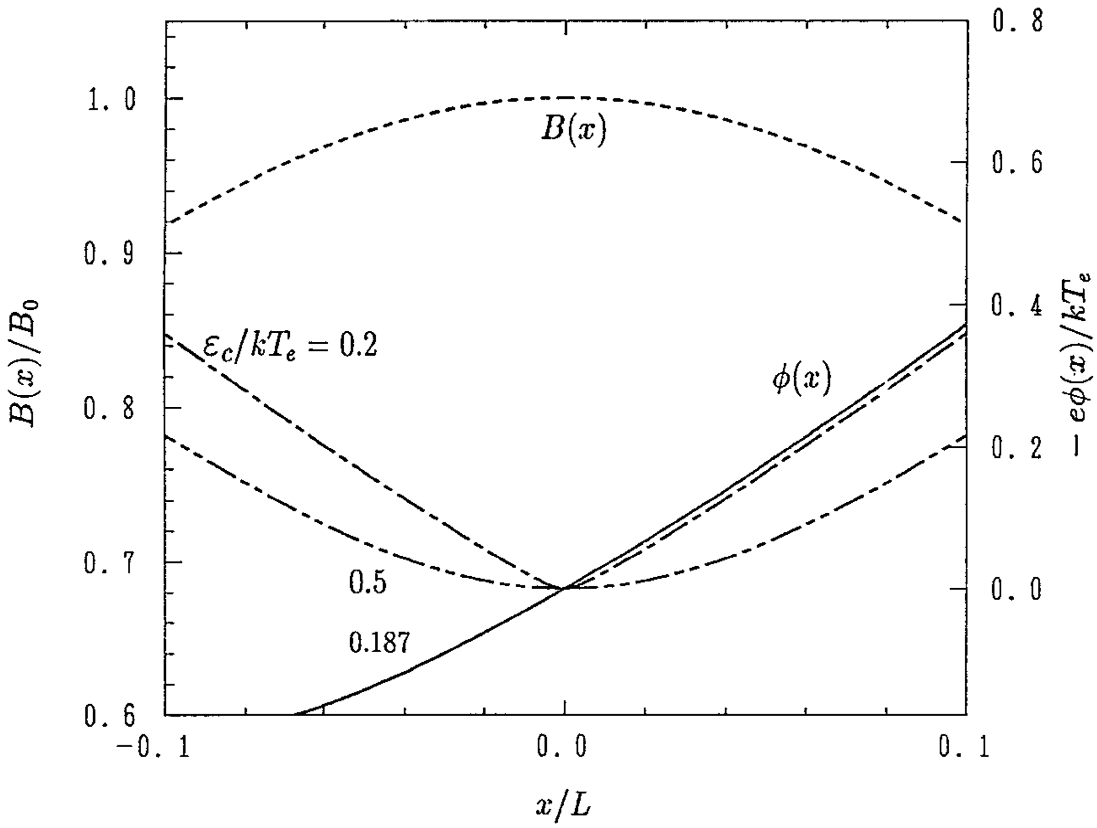

Fig. 6 Potential profile in the vicinity of the magnetic throat for $\varepsilon_c/kT_e = 0.187, 0.2$ and 0.5. Another parameters are $T_i/T_e = 1$ and $\alpha = 0$. The gereralized Bohm criterion is marginally satisfied at the throat when $\varepsilon_c/kT_e = 0.187$.

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