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Subsonic ion flow at the presheath entrance in tokamak divertors

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At the interface between a magnetized plasma and solid surface, a magnetic presheath region exists before the Debye sheath. The subsonic ion flow at the entrance to the magnetic presheath is investigated under divertor-relevant plasma conditions. The collisional sheath problem is investigated with a simple fluid model. Reasonable boundary conditions at the Debye sheath edge are found based on the analysis of the Sagdeev potential. By using a fluid model, the relationship between ion flow at the presheath entrance and the presheath length is evaluated. It is found that the starting value of the ion velocity along the magnetic field lines decreases with the increase of the presheath length for a fixed collisionality, which has a limitation imposed only by the presheath length. Chodura's sonic ion flow is approached when the presheath length $L \rightarrow 0$. For a fixed presheath length, the required ion velocity at the presheath entrance decreases with increasing collisionality. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1562478]

I. INTRODUCTION

In tokamaks, plasma particles are confined by closed magnetic flux surfaces. Outside the last closed flux surface (LCFS), plasma is in direct contact with the target plates of the divertor. In the simplest picture, the particles are removed by transport along the magnetic field in the scrape-off layer (SOL) to the solid surface of the target plates. Such flow results from the pressure gradient that arises along the magnetic field **B** due to the fact that the solid surface is a sink for charged particles, which depresses the local pressure.

At the interface between the plasma and the solid surface, the quasineutral plasma is shielded from a negative absorbing wall by a thin positive space charge region (sheath) with a thickness of several Debye lengths. For a collisionless sheath, Bohm[1] has derived a criterion that the ions must enter the sheath region with a high-directed velocity $V_x \geqslant c_s$, here c_s is the ion acoustic velocity. Consequently, a presheath, where a electric field exists, is required to accelerate the ions to the acoustic velocity perpendicular to the surface at the sheath edge. When a magnetic field at some oblique angle to the solid surface exists in a collisionless plasma, Chodura[2] showed that a magnetic presheath region arises upstream of the Debye sheath and found a criterion of the ion speed along field lines at the "entrance" to the magnetic presheath, i.e., $V_\parallel \geqslant c_s$, and he postulates an additional "plasma presheath" to accelerate ions to the speed of sound. In the divertor SOL analysis, Chodura's claim of a sonic plasma flow along field lines is usually used as a boundary condition.[3–6]

Riemann[7] addressed the presheath issue allowing for the additional effect of ion collisions. By using a hydrodynamic model, he investigated the general presheath mechanism and got a coherent picture for the plasma–sheath transition accounting both for an oblique magnetic field and for collisions. The inclusion of collisions provides a "velocity driver," and the ion acceleration can be accomplished within the magnetic presheath. The ion flow at the presheath entrance is subsonic. The ion velocity at the entrance to the magnetic presheath is an important boundary condition in the models and codes used for both one and two-dimensional SOL analysis. To understand the features of the ion flow at the presheath entrance, in this paper we use the presheath model introduced by Riemann to investigate the relationship of the ion velocity at the presheath edge with respect to the presheath length and collisionality.

A well-defined sheath edge exists only for the asymptotic limit $\alpha = \lambda_D / \lambda_i \rightarrow 0$, where λ_i and λ_D are the ion mean free path and Debye length, respectively. In the asymptotic theory, the sheath edge is defined by a singularity of the electric field terminating the quasineutral presheath. Due to the singularity, a smooth match of the presheath and sheath solutions is impossible. In real tokamak plasmas, ion collisions in the sheath cannot always be ignored and the value of λ_D / λ_i should be finite. To account for the collision effects, an attempt has been made to analyze the plasma sheath transition on an "intermediate scale." [8] This clears up some misunderstandings on the plasma–sheath concept, but it is valid only for the case of $\alpha \ll 1$. In order to be consistent with the presheath analysis accounting for collisions, here we will give a group of more reasonable boundary conditions for a collisional sheath by using a method based on the analogy of the motion of a classical particle in a potential well presented in the previous work.[9]

In the next section the model of magnetic presheath is described, and an analysis for a collision-free presheath based on the equation of energy conservation law is presented. In Sec. III the collisional sheath boundary conditions are derived by analogy to the analysis of a classical particle in a potential well. In Sec. IV the subsonic ion flow at the presheath entrance is discussed in more detail by numerically integrating the fluid equations for the presheath, and in the last section the summary is presented.

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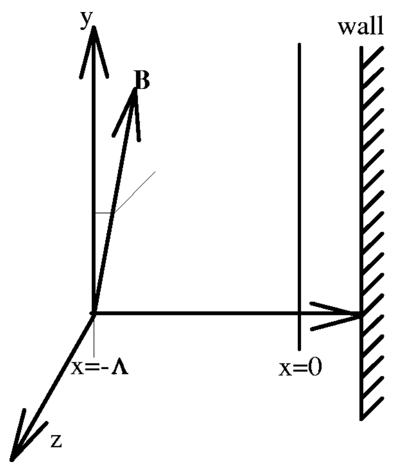

FIG. 1. Geometry for the plasma–wall transition model. The magnetic field vector is in the $x-y$ plane and $x=-\Lambda$ indicates the entrance to the magnetic presheath, $x=0$ the sheath edge.

II. MODEL OF MAGNETIC PRESHEATH

We use the presheath model introduced by Riemann.[7] A fluid model governs the motion of ions,

$$\nabla\cdot(n_i\mathbf{V})=0, \tag{1}$$

$$m_i\mathbf{V}\cdot\nabla\mathbf{V}=e(\mathbf{E}+\mathbf{V}\times\mathbf{B})-\frac{1}{n_i}\nabla p_i-\nu_c m_i\mathbf{V}, \tag{2}$$

$$\nabla p_i=\gamma T_i\nabla n_i, \tag{3}$$

where m_i, T_i, and n_i are the ion mass, temperature, and density, respectively, $\mathbf{V}$ is the average ion flow velocity, ∇p_i is the ion pressure gradient with the adiabatic ratio γ, and ν_c is the effective ion collision frequency used to show the plasma collision effects. Furthermore, it is assumed that the ion flow is isothermal, and the plasma is in the condition of quasineutrality (i.e., the plasma on the presheath scale $\Lambda \gg \lambda_D$) and of Boltzmann equilibrium of the electrons,

$$n_i=n_e=n_0\exp(e\phi/T_e), \tag{4}$$

where T_e is the electron temperature, and n_0 is the charged particle density at the sheath edge (where $\phi=0$).

The geometry of the model for the magnetic presheath is shown in Fig. 1. The plasma state is assumed to depend on the coordinate perpendicular to the wall only. The electric field $\mathbf{E}=-\nabla\phi$ is parallel to the x direction. The magnetic field $\mathbf{B}$, which is in the $x-y$ plane, is assumed to be static and homogeneous. The $x=0$ plane separates the presheath ($x<0$) from the sheath ($x>0$) that extends several Debye length λ_D to the particle absorbing wall. $x=-\Lambda$ (which is not well defined) presents the entrance to the magnetic presheath. By using the notations

$$\delta=\frac{\omega_x}{\omega_y}=\tan\theta,\quad \nu=\frac{\nu_c}{\omega_y},\quad \varsigma=x/\rho_i, \tag{5}$$

$$\dot{x}=V_x/c_s,\quad \dot{y}=V_y/c_s,\quad \dot{z}=V_z/c_s,\quad \chi=e\phi/T_e, \tag{6}$$

where $\boldsymbol{\omega}=e\mathbf{B}/m_i$, $c_s^2=(T_e+\gamma T_i)/m_i$, $\rho_i=c_s/\omega_y$, the dimensionless governing equations are obtained,

$$\left(\dot{x}-\frac{1}{\dot{x}}\right)\dot{x}'=-\dot{z}-\nu\dot{x}, \tag{7a}$$

$$\dot{x}\dot{y}'=\delta\dot{z}-\nu\dot{y}, \tag{7b}$$

$$\dot{x}\dot{z}'=\dot{x}-\delta\dot{y}-\nu\dot{z}, \tag{7c}$$

where the prime indicates derivative with respect to ς. The dimensionless potential is related to the flow velocity by

$$\chi=\ln(1/\dot{x}). \tag{8}$$

When collision is neglected, the energy conservation law is obtained by integrating Eqs. (7),

$$\dot{x}^2+\dot{y}^2+\dot{z}^2=2\ln\frac{\dot{x}}{\dot{x}_L}+u, \tag{9}$$

where $u(=V_{\parallel L}/c_s)$ and $\dot{x}_L$ are the ion velocity along the magnetic field and the x component of ion velocity at the presheath entrance ($\varsigma=-L\equiv-\Lambda/\rho_i$), respectively. At the presheath edge defined by Chodura, the following boundary conditions exist:

$$\dot{x}_L=u\sin\theta,\quad \dot{y}_L=u\cos\theta,\quad \dot{z}_L=0. \tag{10}$$

From the energy conservation equation (9), it is obtained that

$$\dot{x}'=\frac{\dot{x}}{(1-\dot{x}^2)}\sqrt{f(\dot{x},u)} \tag{11}$$

with

$$f(\dot{x},u)=u^2+2\ln(\dot{x}/\dot{x}_L)-\dot{x}^2 -\left[\frac{u+1/u}{\cos\theta}-(\dot{x}+1/\dot{x})\tan\theta\right]^2. \tag{12}$$

The above equations have been derived by Riemann in Ref. 7, where Chodura's condition for presheath is also derived from the argument that the asymptotic plasma solution from Eq. (11) is only met if $f''(\dot{x}_L,u)\geqslant 0$. Here, we will derive Chodura's presheath criterion by analyzing an analogous Sagdeev potential of a classical particle, which leads to the same result as in Ref. 7. Substituting Eq. (8) into Eq. (11) yields

$$\chi'^2+V(\chi,u)=0, \tag{13}$$

where

$$V(\chi,u)=-f(\dot{x}(\chi),u)/(1-e^{-2\chi})^2. \tag{14}$$

Equation (13) is analogous to the energy conservation law for a classical particle in the potential well $V(\chi,u)$. The residual electric potential in the presheath decreases monotonically from $\chi=-\ln\dot{x}_L$ at the presheath entrance to $\chi=0$ at the sheath edge generally, which requires that $\chi'\leqslant 0$ all over the presheath. By analogy of the analysis of a particle in a potential well, the Sagdeev potential should satisfy the condition,

$$V(\chi,u)\leqslant 0. \tag{15}$$

The extreme value of $V(\chi,u)$ is obtained when

$$\frac{\partial}{\partial \chi} V(\chi,u) = \frac{4e^{-2\chi} f(\dot{x}(\chi),u) + e^{-\chi}(1-e^{2\chi})\partial f/\partial \dot{x}}{(1-e^{-2\chi})^3} = 0. \tag{16}$$

Since $f(\dot{x}_L) = \partial f(\dot{x}_L)/\partial \dot{x} = 0$, the Sagdeev potential has its extreme value $V(\chi_L,u)=0$ at $\chi_L = -\ln \dot{x}_L$. Taking into account the second order derivative of $V(\chi,u)$ at χ_L,

$$\frac{\partial^2 V(\chi_L,u)}{\partial \chi^2} = -\frac{2\delta^2(e^{2\chi_L}-1)}{(1-e^{-2\chi_L})^2}(u^2-1), \tag{17}$$

the required condition for the Sagdeev potential, Eq. (15) is only met if $u \geqslant 1$. This equation is the same as Eq. (23) in Ref. 7.

For the collision-free presheath, the ion velocity perpendicular to the wall $\dot{x}$ rises rapidly in a narrow region approaching the Debye sheath.[2] At the first rise of $\dot{x}$ in the presheath, $\Delta = (\dot{x}-\dot{x}_L)/\dot{x}_L \ll 1$. When Chodura's criterion $u = 1$ is used, to the lowest order of Δ, Eq. (11) is approximated by

$$\dot{x}'^2 = \frac{2}{3}\frac{\dot{x}_L^2}{(1-\dot{x}_L^2)^2}\Delta^3. \tag{18}$$

Integrating the above equation, for large values of $|\varsigma|$ an approximated solution is obtained,

$$\varsigma = -\sqrt{6}\frac{(1-\dot{x}_L^2)}{\sqrt{(\dot{x}-\dot{x}_L)/\dot{x}_L}}. \tag{19}$$

Equation (19) results in the asymptotic solution $\varsigma \to -\infty$ for $\dot{x} \to \dot{x}_L$, i.e., the presheath edge moving to infinitive, which is also indicated in Ref. 7.

For tokamaks, the toroidal magnetic field is very strong and $\nu \ll 1$. Chodura's claim of a sonic plasma flow along the field lines seems reasonable and is usually used as a boundary condition in the SOL analysis. However, the neglect of collisions moves Chodura's sonic point to $x \to -\infty$.

III. BOUNDARY CONDITIONS OF A COLLISIONAL SHEATH

Here we use the sheath model presented in Ref. 8. Ions obey the cold fluid equations,

$$n_i V_x = j_i, \tag{20}$$

$$m_i V_x \frac{dV_x}{dx} = -e\frac{d\phi}{dx} - \nu_c(V_x) m_i V_x, \tag{21}$$

where j_i is a constant that is free to choose $j_i = n_0 c_s$. The charge exchange is assumed to be the main ion friction and a constant mean free path λ_i is used, $\nu_c(V_x) = V_x/\lambda_i$. Assuming Boltzmann distributed electrons, their density is given by Eq. (4). The electric potential is governed by Poisson's equation,

$$e(n_i - n_e) = -\varepsilon_0 d^2\phi/dx^2, \tag{22}$$

where ε_0 is the permittivity. The normalization in Eq. (6) is used, but the Debye length λ_D is used here to define the natural measure for distance $(\bar{\varsigma} = x/\lambda_D)$, yielding the basic equations

$$\dot{x}\dot{x}' + \chi' = -\alpha \dot{x}^2, \tag{23}$$

$$\chi'' = \exp \chi - 1/\dot{x}, \tag{24}$$

where $\alpha = \lambda_D/\lambda_i$ indicates the collision effects, and the prime designates derivative with respect to $\bar{\varsigma}$.

In the presheath the quasineutrality relation Eq. (8) can be used as a zeroth order approximation. Introducing it into Eqs. (23)–(24), we obtain the first order approximation

$$\chi = \ln[1/\dot{x} - 2\alpha^2\dot{x}^4/(1-\dot{x}^2)^3], \tag{25}$$

$$\chi' = -\alpha \dot{x}^2/(1-\dot{x}^2). \tag{26}$$

It means that space charges occur everywhere in the environment of the sheath, and the space charge density is dependent on the collisionality and ion velocity,

$$\rho_s = \frac{2\alpha^2\dot{x}^4}{(1-\dot{x}^2)^3} n_0 e. \tag{27}$$

Assuming that they are also valid at the sheath edge, the boundary condition at the sheath edge is produced,

$$\chi_0 = \ln[1/M - 2\alpha^2 M^4/(1-M^2)^3], \tag{28}$$

$$\chi_0' = -\alpha M^2/(1-M^2), \tag{29}$$

where M is the Mach number of ions at the sheath edge $(\dot{x}_0 = M)$, that should be determined reasonably.

Integrating the Poisson's equation in the sheath region once, yielding

$$1/2(\chi')^2 + U(\chi,M) = 1/2(\chi_0')^2, \tag{30}$$

where the Sagdeev potential is

$$U(\chi,M) = \int_0^{\bar{\varsigma}} \chi'(1/\dot{x} - \exp\chi)\, d\varsigma, \tag{31}$$

Eq. (30), like Eq. (13) in Sec. II, is also an analogy to the energy conservation law of a classical particle in the potential well $U(\chi,M)$ with the total energy being $1/2(\chi_0')^2$. It is well known that for the existence of a positive sheath, a monotonic χ' with $\chi' \leqslant 0$ is required everywhere all over the sheath. By analogy to the motion of a particle in a potential well, it needs

$$U(\chi,M) \leqslant (\chi_0')^2/2 \tag{32}$$

in the sheath, which means that the Mach number of ions at the sheath edge has limitations, and the limitation is the sheath criterion. The Sagdeev potentials with $\alpha = 0.1$, and $M = 0.35$, 0.467, and 0.75, which correspond to the cases of $U_m > (\chi_0')^2/2$, $U_m = (\chi_0')^2/2$, and $U_m < (\chi_0')^2/2$, respectively [where U_m is the maximum of $U(\chi,M)$], are shown in Fig. 2, where the corresponding analogous total energy $(\chi_0')^2/2$ is also shown with horizontal straight lines. It is demonstrated from Fig. 2 that there is really a limitation for M. Figure 3 presents the relationship between M and α that satisfies the equality $U_m = (\chi_0')^2/2$. The regression method is used to get the solid line in Fig. 3 that will be used afterward to determine the Mach number at the sheath edge with certain collisionality.

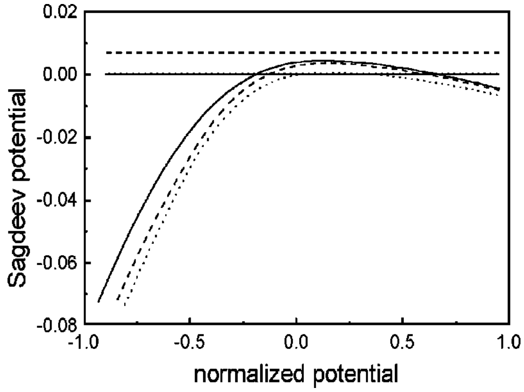

FIG. 2. Sagdeev potential U and the corresponding total energy $\chi_0'^2/2$ (horizontal straight lines) vs the normalized potential for $\alpha=0.1$, and $M=0.35$ (solid line), 0.467 (dotted line), and 0.75 (dashed line), which correspond to the cases of $U_m>(\chi_0')^2/2$, $U_m=(\chi_0')^2/2$, and $U_m<(\chi_0')^2/2$, respectively.

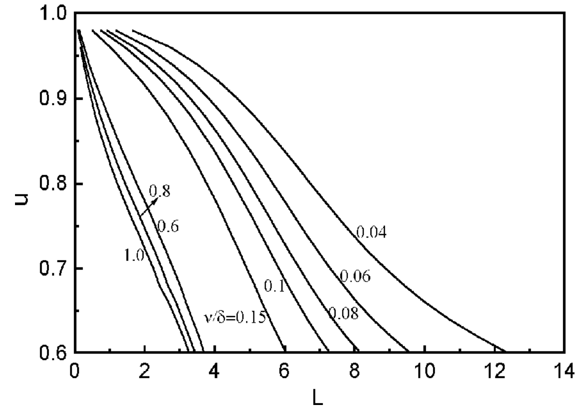

FIG. 4. Ion velocity at the presheath edge u vs the presheath length L for $\delta=0.1$ and various values of ν/δ (0.04–0.15 and 0.6–1.0). Boundary condition Eq. (33) is used.

IV. ION FLOW AT THE PRESHEATH ENTRANCE

As indicated by the analysis above, the neglect of collisions moves Chodura's sonic point to $x\rightarrow-\infty$. The presheath edge and ion velocity at the edge could not be well defined for a collisional magnetic presheath. If we shift the presheath boundary to the sheath edge, what results can we get? The sheath criterion should be satisfied certainly. The other two components of ion velocity still have to be obtained from the presheath analysis. Thus the analysis for the boundary conditions at the entrance to the magnetic presheath is necessary for the SOL models. The components of the ion velocity in presheath have been calculated in Ref. 7 for two small values of the oblique angle θ and various collisionalities. Here we will evaluate the ion velocity along the magnetic field at the presheath entrance by integrating the presheath equations numerically.

To solve the presheath equations, we utilize a shifted space coordinate ($\varsigma\rightarrow\hat{\varsigma}=\varsigma+L$) and integrate Eqs. (7) in the positive $\hat{\varsigma}$ direction. To this end we need the initial values of $\dot{x}$, $\dot{y}$, and $\dot{z}$ at the presheath entrance $\varsigma=-L$ ($\hat{\varsigma}=0$). In the tokamak SOL, generally $\nu\ll\delta\ll1$. The ion flow at entrance to the magnetic presheath can be considered as being composed of a motion along the magnetic field lines and an $\mathbf{E}\times\mathbf{B}$ drift, as discussed by Riemann,[7]

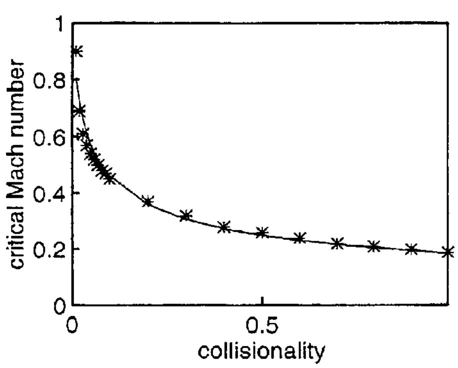

FIG. 3. Mach number M at the sheath edge, which satisfies $U_m=\chi_0'^2/2$, as a function of collisionality α (stars). The solid line is the simulated result with the regression method.

$$\dot{x}_L=u\sin\theta,\quad \dot{y}_L=u\cos\theta,$$
$$\dot{z}_L=\frac{\nu}{\delta}\frac{u\cos\theta}{1-(1+\delta^2)u^2\cos^2\theta}. \tag{33}$$

By solving Eq. (7) we find that the ion motion in y direction, which is almost parallel to the magnetic field, can be written as a quadratic algebra equation,

$$\dot{y}^2-[(u+1/u)\cos\theta-\xi]\dot{y}+1/(1+\delta^2)=0, \tag{34}$$

where $\xi=(\nu/\delta)\hat{\varsigma}$ is small. While approaching the presheath entrance ($\hat{\varsigma}\rightarrow0$), Eq. (34) yields a physical solution at the presheath edge only if

$$F(u)=u+1/u\geqslant2. \tag{35}$$

At the sonic point ($u=1$), the function $F(u)$ is of minimum $F_{\min}=2$, and the boundary condition Eq. (33) exhibits singularity at the sonic point. Consequently, the ion motion in y direction has two different branches: one is supersonic $u>1$, and another subsonic $u<1$. Only the subsonic branch yields a reasonable physical approximation.

It has been known that the function of the presheath is to accelerate the ion velocity perpendicular to the wall from $\dot{x}_L=u\sin\theta$ at the presheath edge to $\dot{x}_0=M$ at the sheath edge. There must be a relationship between the ion velocity at the presheath entrance and the presheath length L in which the acceleration is accomplished. We apply a Runge–Kutta procedure to integrate Eqs. (7). The integration is continued until we reach the sheath edge where the ion velocity perpendicular to the wall is equal to that determined by the relationship between M and α shown in Fig. 3. We choose $\delta=0.1$, which corresponds to $B_p/B_T=0.1$ in tokamaks, where B_p and B_T is the poloidal and toroidal magnetic field, respectively. For a hydrogen plasma, $\lambda_D/\rho_i=0.1$ is roughly consistent with the value obtained in the tokamak SOL. When the case with $\gamma=1$ (isothermal ion flow) and $T_i/T_e=1$ is taken, the functional relation of the requested ion velocity along the magnetic field at the presheath edge u with respect to the presheath length L is obtained (Fig. 4). The two groups of curves in Fig. 4 correspond to two different collisionality regimes: $\nu/\delta=0.04-0.15$ corresponding to the case of $\nu\ll\delta$, and $\nu/\delta=0.6-1.0$ corresponding to $\nu\sim\delta$. It is

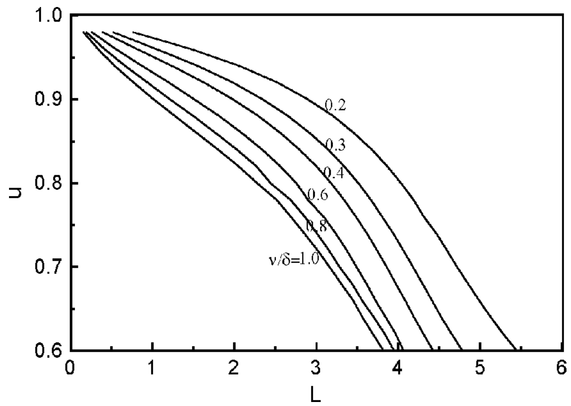

FIG. 5. Ion velocity at the presheath edge u vs the presheath length L for $\delta=0.1$ and various values of ν/δ (0.2–1.0). Boundary condition Eq. (37) is used.

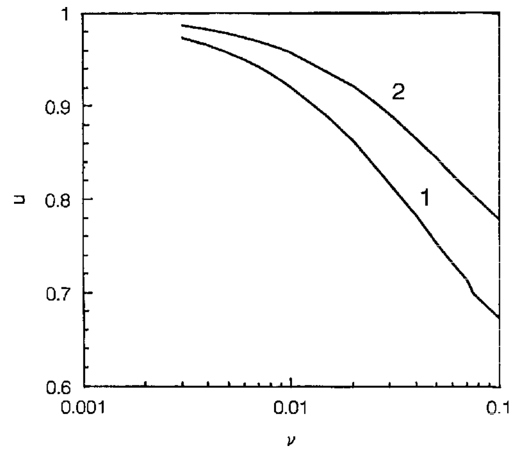

FIG. 6. Ion velocity at the presheath edge u as a function of the effective collision frequency ν for $L=2.5$, curve 1 and 2 corresponding to boundary condition Eq. (33) and Eq. (37), respectively.

found that the starting value of the ion velocity along the magnetic field line decreases with the increasing of the presheath length for a fixed collisionality. Chodura's sonic ion flow along magnetic field is approached only when $L \to 0$. The effect of friction on ion acceleration is obvious: even if the ion velocity perpendicular to the wall at the presheath entrance ($\dot{x}=u \sin\theta$) is very small, it can be accelerated to the value that satisfies the sheath criterion after passing through the presheath. With increasing collision frequency, the ion velocity drop increases due to the collision driving. If the collision frequency is further increased to the case of $\nu \sim \delta$, the function forms are changed significantly, as displayed by the two groups of curves in Fig. 4.

When the neutral density near the solid surface is extremely high, e.g., nearby the target plate of detached divertors, or when the grazing angle of the magnetic field is very small, the above consideration of the ion flow at the entrance [Eq. (33)] will not hold. In these situations, $\nu \sim \delta \ll 1$, and the ion flow diverges a little from the magnetic field. It can be assumed that the ion flow in the z direction is just an $\mathbf{E}\times\mathbf{B}$ drift caused by the local electric field of the presheath, i.e.,

$$\dot{z}_L = \frac{\cos^2\theta}{(1+\gamma T_i/T_e)} \dot{x}'_L/\dot{x}_L . \tag{36}$$

By using Eqs. (7), we obtain the value of $\dot{z}$ at the presheath edge as a function of u,

$$\dot{z}_L = \frac{\nu u \sin\theta}{(1+\gamma T_i/T_e)\,\delta^2(1-u^2)} . \tag{37}$$

The boundary condition is still singular at the sonic point. The same procedures used to achieve the results shown in Fig. 4 is carried on with the new form of boundary conditions, and the corresponding results are obtained (Fig. 5). Here the same parameters are used as above, but the collisionalities are taken in the regime closing to δ. It is shown that when the new boundary conditions are used, the requested ion velocity along the magnetic field at the presheath edge is of similar functional relationship as in the case of low collisionality in Fig. 4. Even if $\nu \sim \delta$, the function form remains similar.

The intrinsic presheath indicated by a strongly inhomogeneous potential variation has an extension of several ion gyroradii. When the collision is neglected, from Eq. (19) we obtain

$$\frac{\dot{x}-\dot{x}_L}{\dot{x}_L} = \left(\frac{L_m}{x}\right)^2 , \tag{38}$$

with $L_m=\sqrt{6}\rho_i \cos^2\theta$, the Chodura's criterion $u=1$ is used here. As analyzed in Ref. 2, the scale length, L_m, is the potential variation scaling in presheath. We take this scale length as the presheath length. For a fixed presheath length ($L=2.5$), the relationship of the ion flow with respect to the effective collisions is evaluated as presented in Fig. 6 in which the curve 1 and 2 correspond to boundary conditions (33) and (37), respectively. It is shown that as the presheath length is fixed the required ion velocity at the presheath entrance decreases with increasing collisionality, and the difference between curve 1 and curve 2 becomes bigger when collision frequency increases.

V. SUMMARY

When a magnetic field at some oblique angle to the solid surface is present in plasmas, a magnetic presheath region arises upstream of the Debye sheath. According to the analysis without accounting for ion collisions, the condition of (super)sonic ion flow along the field lines at the entrance of the magnetic presheath was found, and the acoustic velocity is usually used as a boundary condition in both one and two-dimensional SOL analysis. Since the ion friction is neglected completely, in this approximation it is impossible to pass the sound barrier, and reasonable solutions only for the supersonic regime were obtained. The inclusion of collisions provides a "velocity driver," and subsonic ion flow at the presheath entrance is obtained.

The fluid model[7] is used in the magnetic presheath analysis. When the collision effect is neglected, the energy conservation law is obtained from the fluid equations. Based on the energy conservation equation, an analysis for the collision-free presheath is carried out. Analyzing an analogous Sagdeev potential for a classical particle derives Chodura's presheath criterion. For large $|\varsigma|$ values, an approximate explicit expression of $\dot{x}$ with respect to ς is obtained, which results in the asymptotic solution $\varsigma \rightarrow -\infty$ for $\dot{x} \rightarrow \dot{x}_L$, i.e., the presheath edge moving to infinitive for the sonic ion flow.

To be consistent with the plasma–wall transition scenario in collision-dominated plasmas, the collisional sheath problem is investigated with a simple fluid model. The space charges occur everywhere around the sheath edge, as indicated by Riemann,[8] and the sheath edge is not defined by the point where the first space charges occur but at the point where space charge effects become dominant. A group of reasonable boundary conditions are found for the collisional sheath edge based on the analysis of the Sagdeev potential.

The subsonic ion flow at the entrance to the magnetic presheath is investigated under divertor-relevant plasma conditions. Generally in the tokamak SOL, the ion flow at the entrance to the magnetic presheath can be considered as being composed of a motion along the magnetic field line and an $\mathbf{E}\times\mathbf{B}$ drift.[7] The relationship between the starting value of the ion flow and the presheath length is evaluated by numerically integrating the presheath equations [Eq. (7)]. It is found that the starting value of the ion velocity along the magnetic field lines decreases as the presheath length increases for a fixed collisionality. Chodura's sonic ion flow is approached when the presheath length $L\rightarrow 0$. Instead of employing the collisional sheath boundary condition shown in Fig. 3, we also integrate Eqs. (7) forwards until the Bohm criterion $\dot{x}_0 = 1$ is approached, and the computed relationship between the starting value of the ion flow and the presheath length remains nearly the same for the values of interest of collision because the normalized velocity to the wall increases rapidly while closing to the sheath edge. However, the singularity in Eq. (7a) is avoided when the collisional sheath boundary condition is used.

When the neutral density near the solid surface is extremely high, Riemann's consideration of ion flow at the presheath edge could not hold. We assume that the ion flow in the direction perpendicular to the magnetic field is just an $\mathbf{E}\times\mathbf{B}$ drift caused by the local electric field in presheath. By using the new form of boundary conditions, the computation results show that when collisionality is low ($\nu \ll \delta$) the requested ion velocity at the entrance of presheath is of similar functional relationship against the presheath length as that by using the previous boundary condition Eq. (33). When the collision frequency ν is close to δ, however, the function form obtained with the boundary condition Eq. (37) remains similar, but that obtained with the boundary condition Eq. (33) changes significantly.

When the field lines intersect the wall at an angle $\theta \neq 0$, the ion transport to the wall is strongly impeded by the magnetic field. A numerical study on the interaction of plasma with fixed wall using the kinetic model[10] has shown that the whole sheath length increases for small incidences of the magnetic field, while the Debye sheath length remains the same. Neglecting the collision effects, a scale length derived from an approximate expression of $\dot{x}$, which has stronger dependence on angle θ than Chodura's,[2] is used as the presheath length. For a fixed presheath length, the requested ion velocity at the presheath entrance decreases with increasing collisionality. We should point out that the ion collision, which is coupled with the ion flow, affects the presheath length as well.

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