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A kinetic trajectory simulation model for magnetized plasma sheath

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Abstract
The plasma-sheath region in an oblique magnetic field has been studied using a kinetic trajectory simulation model. It has been observed that the magnetized plasma-sheath region has two distinct regions: magnetic field dominant region lying close to the sheath entrance and electric field dominant region (almost no effect of magnetic field) lying close to the wall. The particle densities and potential decrease as we move towards the wall, which becomes prominent as the strength and obliqueness of the magnetic field increase. Our results agree well with previous works from other models and hence, we expect our model to provide a basis for studying all types of magnetized plasmas, using the kinetic approach.

1. Introduction

The interaction of plasma with solid material surface is a very important and recent field of research in plasma physics. The study of sheath formation between magnetized plasma and a charged wall has received considerable attention in recent years [1–4]. The main importance of this study is to see the change in the particle dynamics as well as the particle wall interaction in magnetized plasma sheath. Irrespective of this, plasma sheath is significantly influencing the charged particles and the energy flux to the wall, which in turn considerably modifies the absorption, emission impurities and all other characteristics in the plasma [5].

In all practical cases, when the plasma is confined in any closed surface, it is obvious that the plasma interacts with the material surfaces so that the proper understanding of this interaction with the material surface is very important in all plasma applications (e.g. plasma confinement for fusion, sputtering, etching, laboratory discharging, surface treatment, etc) [6]. Once the plasma–wall interaction is well understood it will be possible to control heat loading, energy transfer and particle flow towards the wall and overall bulk plasma behaviour [7, 8].

The 'sheath' structure formed adjacent to a material surface (wall) facing plasma contributes to the stability of the bulk plasma. This usual case, however, runs into a fundamental complication: the considerable distortion of the ion distribution due to wall losses makes shielding impossible unless the 'Bohm criterion' is fulfilled. This condition for sheath formation demands that the ions enter the sheath region with a high velocity, which cannot be generated by thermal ion motion [7]. In its kinetic form for the case of either without magnetic field or magnetic field perpendicular to the wall, this criterion reads

$$\left\langle \frac{1}{v^2} \right\rangle \leqslant \frac{m^i}{k(\gamma_{\rm ps}^{\rm i} T_{\rm ps}^{\rm i} + \gamma_{\rm ps}^{\rm e} T_{\rm ps}^{\rm e})} = \frac{1}{c_{\rm s}^2}, \tag{1}$$

where k is the Boltzmann constant, $\gamma_{\rm ps}^{\rm i}$ and $\gamma_{\rm ps}^{\rm e}$ are the ion and electron polytropic constants, respectively, $T_{\rm ps}^{\rm i}$ and $T_{\rm ps}^{\rm e}$ are the ion and electron temperatures at the presheath side of the sheath edge and $c_{\rm s}$ is the ion acoustic velocity, respectively [7, 8]. In the case of an oblique magnetic field, for the smooth start of the particle at plasma side the velocity of the in-streaming plasma v has to exceed a certain limit,

$$\text{i.e. } v \geqslant c_{\rm s} \cos\psi \tag{2}$$

where ψ is the angle made by the magnetic field with the normal to the surface [9].

In this work, we have studied the magnetized plasma-sheath region formed adjacent to an absorbing wall with presheath plasma on the other side. We have checked the dependence of ion density, electron density and potential in the sheath region on magnitude and obliqueness of the magnetic field. We use the kinetic trajectory simulation (KTS) model [10] to obtain the solution to a non-neutral, time-independent, collisionless plasma sheath using MATLAB. It has been observed that the sheath structure is highly influenced by varying the magnitude and orientation (obliqueness) of magnetic field.

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2. Basic principle of KTS

KTS is an iterative method for numerically calculating self-consistent, time independent kinetic plasma states in some given bounded spatial region. The characteristics features of KTS is that the distribution function of particle species involved are directly calculated by solving the related kinetic equations along the respective collisionless particle trajectory. In order to obtain the distribution function at any point $(\vec{x}, \vec{v})$ of the phase-space, we trace the related trajectories of phase-space where the distribution function is known. Here we assume the velocity distribution function of electrons and ions at the sheath edge to be cut-off Maxwellian in such a way that the most important requirement of the presheath–sheath transition is satisfied, i.e. quasineutrality, the sheath-edge singularity condition, continuity of the first three moments of each species, and the kinetic Bohm criterion [10].

In the general case of time-dependent, collisional kinetic theory, the species s velocity distribution function describes the Boltzmann equation:

$$\frac{\mathrm{d}f(\vec{x}, \vec{v}, t)}{\mathrm{d}t} = \left[\frac{\partial}{\partial t} + \vec{v}.\frac{\partial}{\partial \vec{x}} + \vec{a}^s.\frac{\partial}{\partial \vec{v}}\right] f(\vec{x}, \vec{v}, t) = C^s \quad (3)$$

with

$$\vec{a}^s(\vec{x}, \vec{v}, t) = \frac{q^s}{m^s}[\vec{E}(\vec{x}, t) + \vec{v} \times \vec{B}(\vec{x}, t)] \quad (4)$$

where $\vec{E}(\vec{x}, t)$ and $\vec{B}(\vec{x}, t)$ are the macroscopic (i.e. locally averaged) electromagnetic fields, $\vec{a}^s$ is the macroscopic acceleration of species s particles (i.e. it's acceleration in these fields), and C^s is the species s collision term. The kinetic Boltzmann equation (3) for collisionless cases takes the well known from of Vlasov equation

$$\left(\frac{\partial}{\partial t} + \vec{v}.\frac{\partial}{\partial \vec{x}} + \vec{a}^s.\frac{\partial}{\partial \vec{v}}\right) f(\vec{x}, \vec{v}, t) = 0 \quad (5)$$

i.e. $f(\vec{x}, \vec{v}, t) = $ constant. This means that the velocity distribution function is constant for an observer moving along a collisionless trajectory. Hence, the distribution function at every point along the trajectory can be obtained if its value at one point (i.e. at the boundary) is known.

As the presheath and sheath regions have differences in their scale lengths and in the gradients of physical parameters these regions are usually studied separately, using different models and methods [7, 8, 10, 11]. Often the fluid approach is preferred to study the presheath region whereas kinetic approach would be necessary to explain the sheath region because of its sharp gradient. The best and most satisfactory approach would be to simulate the whole plasma system in question self-consistently in a kinetic approach [11]. The major advantage in using kinetic theory lies in the fact that we obtain particle distribution function in the entire sheath region and not only its average quantities, which is the case in fluid theory.

3. The plasma-sheath model

In this work, we restrict ourselves to time independent, collisionless, electromagnetic problems, as is appropriate for

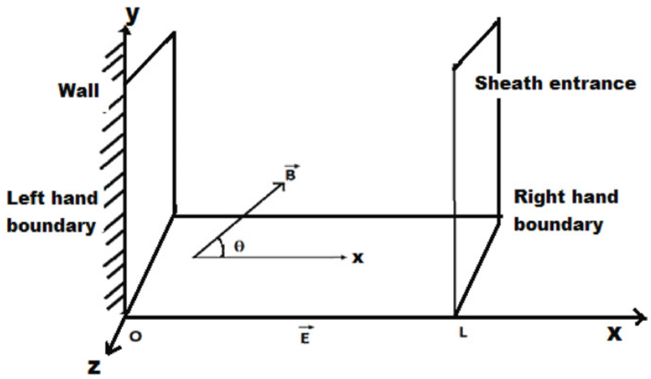

Figure 1. Schematic diagram of the bounded plasma model.

the sheath regions. The 1D3v model of magnetized plasma sheath is shown schematically in figure 1. The notation 1D3v indicates the fact that our model is one-dimensional in configuration and three-dimensional in velocity space.

The region of interest or simulation region considered is bounded by two parallel planes situated at $x = 0$ and $x = L$ and the plasma consists of only electrons and singly charged ions. For simplicity, we have specified as right-hand boundary at $x = L$ as the 'sheath entrance' which separates the non-neutral, collisionless sheath region $(x < L)$ from the quasineutral collisional presheath region $(x > L)$. Similarly, an absorbing wall at $x = 0$ is specified as left-hand boundary. The magnetic field lies in the x–y plane such that

$$\vec{B} = B_0[\cos\theta\,\hat{x} + \sin\theta\,\hat{y}]. \quad (6)$$

We assume the plasma particles (electrons and ions) enter the simulation region from the right-hand boundary with cut-off Maxwellian velocity distribution functions, the left-hand boundary does not emit any particles and that both boundaries are perfectly absorbing. Accordingly, the electron velocity distribution function is given by

$$f^{\mathrm{e}}(x, v) = A^{\mathrm{e}} \exp\left[-\left(\frac{v_x^2 + v_y^2 + v_z^2}{v_{tf}^{\mathrm{e}2}}\right) + \frac{e\phi(x)}{kT^{\mathrm{e}}}\right] \times \Theta[v_{\mathrm{c}}^{\mathrm{e}}(x) - v_x] \quad (7)$$

where

$$v_{\mathrm{c}}^{\mathrm{e}}(x) = \sqrt{\frac{2e[\phi(x) - \phi_0]}{m^{\mathrm{e}}}}$$

is the electron cut-off velocity at x.

The ion velocity distribution function at $x = L$ is given by

$$f^{\mathrm{i}}(L, v) = A^{\mathrm{i}} \exp\left[-\left(\frac{(v_x - v_{\mathrm{m}L}^{\mathrm{i}})^2 + v_y^2 + v_z^2}{v_{tf}^{\mathrm{i}2}}\right)\right] \times \Theta(v_{\mathrm{c}L}^{\mathrm{i}} - v_x) \quad (8)$$

where $v_{tf}^s = \sqrt{2kT^s/m^s}$ is the species s (ion and electron) thermal velocity, $v_{\mathrm{m}L}^{\mathrm{i}}$ is the ion 'Maxwellian-maximum' velocity at $x = L$, $v_{\mathrm{c}L}^{\mathrm{i}}$ ($v_{\mathrm{c}L}^{\mathrm{i}} < 0$) is the ion cut off velocity at $x = L$ and $\Theta(x)$ is the Heaviside function i.e.

$$\Theta(x) = \begin{cases} 1 & \text{if } x \geqslant 0 \\ 0 & \text{otherwise.} \end{cases} \quad (9)$$

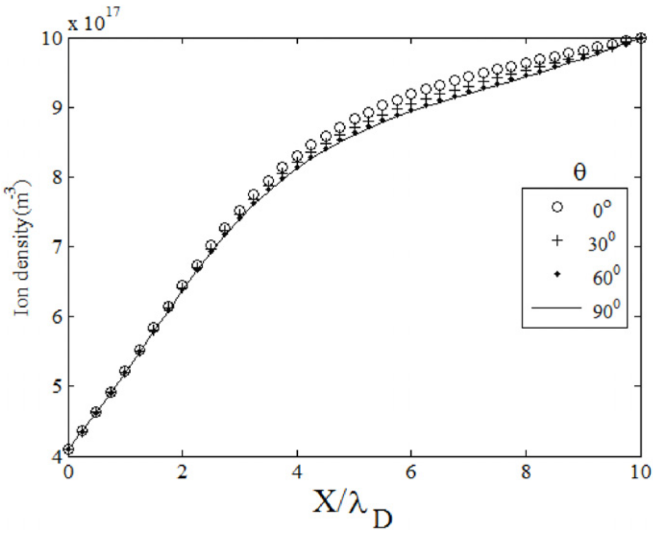

Figure 2. Ion density profile for a magnetic field of 30 mT at different angles.

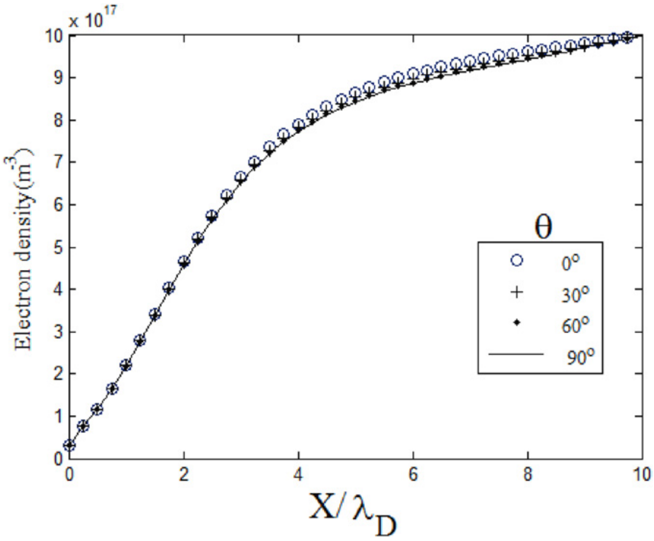

Figure 3. Electron density profile for a magnetic field of 30 mT at different angles.

Here, we have considered the parameter variation only along the x-direction.

In the core plasma the particle distribution would obviously be Maxwellian; however, in the case of sheath formation the ions are accelerated towards the wall so that they become shifted Maxwellian as given by equation (8). In addition, for the Bohm criterion to be satisfied by the ions they must have attained certain minimum velocity (v^{i}_{cL}) at the sheath entrance. As the electrons are retracted and reflected by the negative potential wall their distribution gets cut-off at the sheath entrance as given by equation (7).

The starting parameters for our simulation are the kinetic parameters given at the sheath entrance which can also be calculated for given presheath parameters at the sheath boundary. In case of given presheath parameters we solve a set of presheath–sheath transition equations whose solution yields all necessary kinetic sheath parameters at the sheath entrance as well as the potential at the wall. This method of coupling

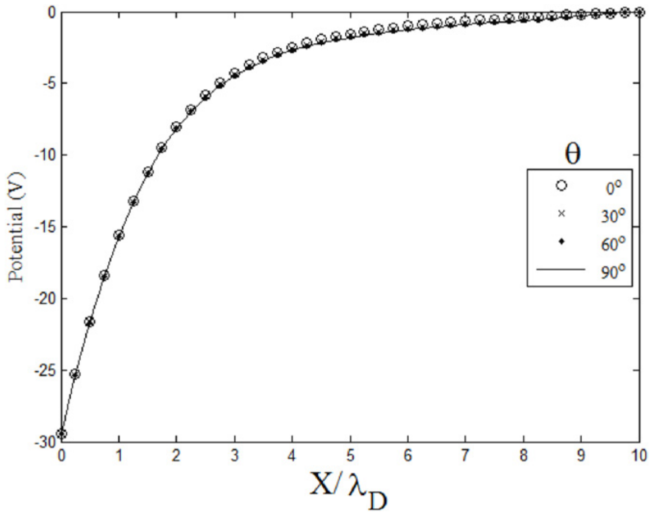

Figure 4. Potential profile for a magnetic field of 30 mT at different angles.

presheath–sheath transition equation has been termed as the 'coupling scheme' [10, 12]. The potential at $x = L$ is always chosen equal to zero and we restrict ourselves to potential distribution $\phi(x)$which decrease monotonically from $\phi = 0$ at $x = L$ to $\phi_{\mathrm{w}} < 0$ at $x = 0$ obtained from the coupling scheme.

Once all the starting parameters at the sheath entrance are known we solve the ion kinetic equations, for different discretized ion injection velocities up to the wall. This gives the ion velocities and their corresponding distribution function in the entire sheath region which on integration yields ion density distribution. The electron density distribution, on the other hand, is calculated analytically using

$$n^{\mathrm{e}}(x) = A^{\mathrm{e}} \int_{-\infty}^{+\infty} \mathrm{d}v_x \int_{-\infty}^{+\infty} \mathrm{d}v_y \int_{-\infty}^{+\infty} \mathrm{d}v_z \times \left[- \left(\frac{v_x^2 + v_y^2 + v_z^2}{v_{tf}^{\mathrm{e}2}} \right) \right] \Theta(v_{cx}^{\mathrm{e}} - v_x) \qquad (10)$$

which yields the electron density in terms of potential as

$$n^{\mathrm{e}}(\phi) = n_L^{\mathrm{e}} \exp\left[\frac{e\phi(x)}{kT_f^{\mathrm{e}}} \right] \left[\frac{1 + \mathrm{erf}\sqrt{e(\phi(x) - \phi_0)/kT_f^{\mathrm{e}}}}{1 + \mathrm{erf}\sqrt{(-e\phi_0)/kT_f^{\mathrm{e}}}} \right]. \qquad (11)$$

Thus obtained ion and electron densities are used in the Poisson equation, which results in a new potential profile. The iteration scheme is iterated unless the final self-consistent results are obtained.

4. Results and discussion

Figures 2 and 3 show the self-consistent particle (ion and electron) density versus distance (normalized with respect to the electron Debye length at the sheath entrance) from the wall for a magnetic field of 30 mT at different angles. From the plot we see that the particle density decreases from sheath entrance towards the wall, where it acquires its minimum.

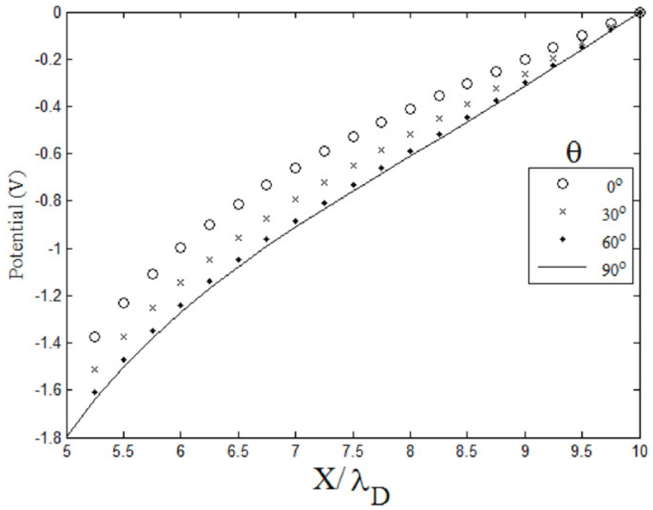

Figure 5. Potential profile for a magnetic field of 30 mT near to the sheath entrance at different angles.

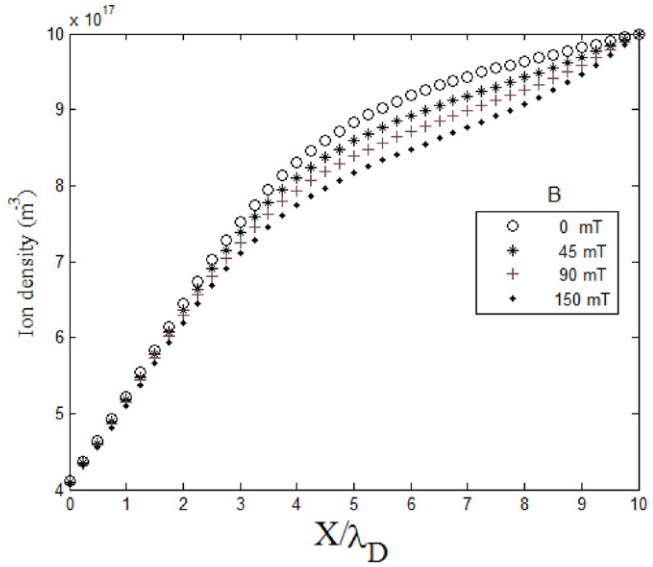

Figure 6. Ion density profile for an oblique magnetic field (45°) of varying magnitude.

As we increase the angle, the particle density drops. This is attributed to the fact that as the angle increases the x component of $(\vec{v} \times \vec{B})$-force also increases, for examples when $\theta = 0°$ the component of force is also zero whereas for $\theta = 90°$ the force is $-qv_zB$, i.e. the force is maximum and acts along the negative x-direction.

Figure 4 shows the self-consistent potential profile for a magnetic field of 30 mT at different angles. From the plot we see that the potential profile has sharp gradient closer to the wall, whereas at the sheath entrance the potential is almost constant, as expected. Blow-up of the region with close to sheath entrance has been shown in figure 5. As we increase the angle, the potential near to the sheath entrance drops, due to the decrease in the ion and electron density densities for the larger angle.

Figures 6 and 7 show the self-consistent particle (ion and electron, respectively) density profile for an oblique magnetic field at 45° of varying magnitude. As we increase the magnetic field, the particle gyrates more and hence decreases the velocity towards the wall. The particle density decreases faster for increasing magnetic field near the sheath entrance but does not changes close to the wall because the electric field dominates over the magnetic field as the particle approaches the wall. As a result the particle density at the wall remains almost unchanged for varying magnetic field.

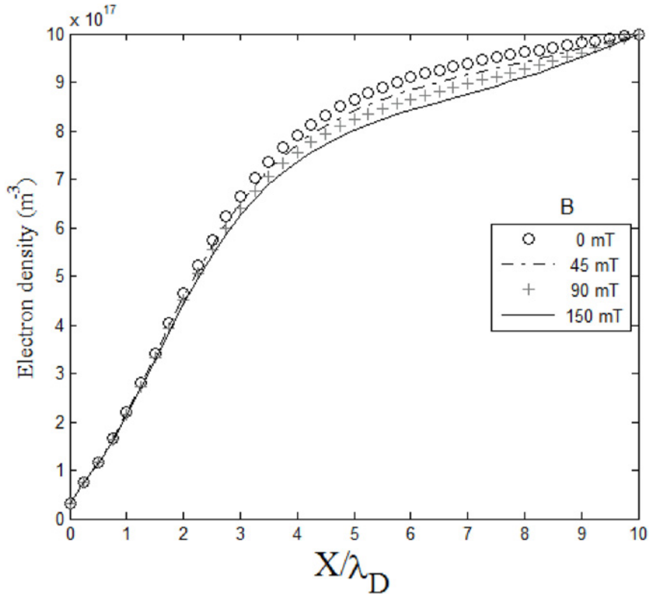

Figure 7. Electron density profile for an oblique magnetic field (45°) of varying magnitude.

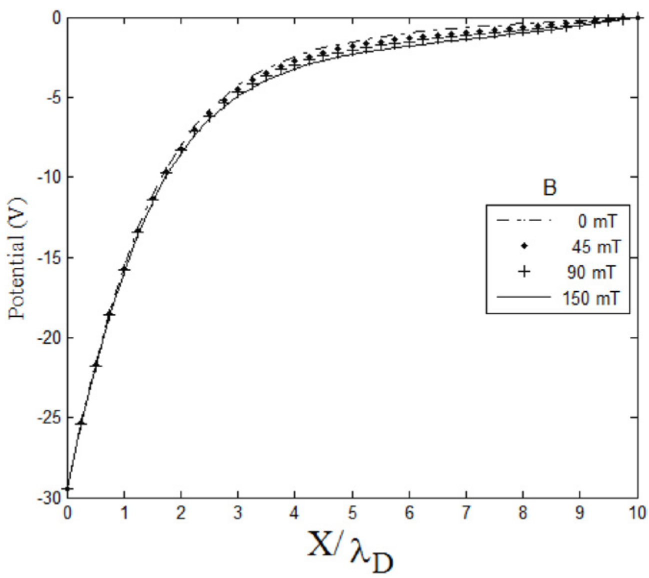

Figure 8. Potential profile for an oblique magnetic field (45°) of varying magnitude.

Figure 8 shows the self-consistent potential profile for an oblique magnetic field at 45° of varying magnitude. From the plot we see that as the magnitude of the magnetic field increases, the potential decreases. The increased magnetic field causes the ion and electron densities to decrease, especially in the region close to the sheath entrance which causes also the potential to decrease. The potential at the wall

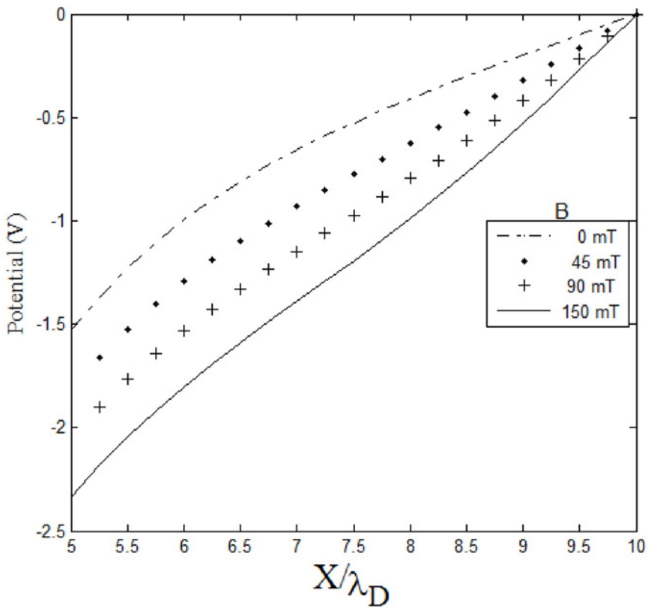

Figure 9. Potential profile near to the sheath entrance for an oblique magnetic field (45°) of varying magnitude.

remains almost insensitive for varying magnetic field. Figure 9 shows the potential profile close to the sheath entrance, where its effect is prominent.

5. Conclusion

It has been observed that the magnetic effect is prominent near to the sheath entrance and has almost no effect at the wall. This shows that the magnetized plasma sheath has two distinct regions: magnetic field dominant region lying close to the sheath entrance and electric field dominant region (almost no effect of magnetic field) lying close to the wall. In the magnetic field dominant region, particles are accelerated by a weak electric field and gyrated by magnetic field. As a result their path changes continuously which decreases their velocity towards the wall. These two regions are often referred to as magnetic presheath and electrostatic Debye sheath. These results are in good agreement with previous works [4, 9, 10] following different approaches and hence our work is expected to provide a basis for studying magnetized plasma sheath using the kinetic approach.

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