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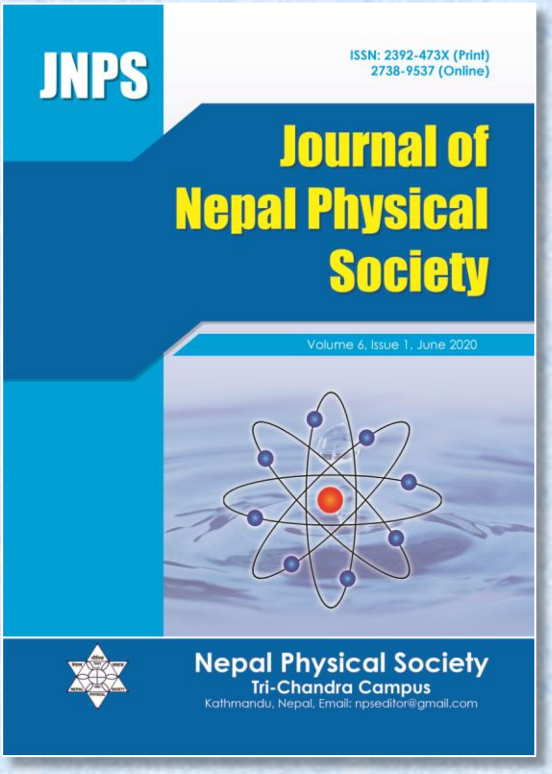

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Research Article

Variation of Velocity of Ions in a Magnetized Plasma Sheath for Different Magnetic Field

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Abstract

The kinetic trajectory simulation method has been used to study ion velocity profile in a plasma sheath for varying magnetic field at fixed obliqueness. As the electrons have higher velocity compared to that of ions the wall is charged up negatively with respect to the core plasma. The negative potential then attracts the ions and repels electrons forming a thin positive space charge region in front of the wall. This positive space charge region, known as the 'sheath' separates the negatively charged wall from the quasineutral 'presheath' plasma. The ions moving towards the wall have to satisfy the Bohm criterion to ensure the stability of the overall plasma. The mean value as well as oscillation frequency of velocity of ions change as the magnetic field is varied from 1.5 to 10.5 mT. The maximum amplitude of normal component of velocity is almost independent of the magnetic field but the maximum amplitude of other components of velocity change and shows oscillating nature as the magnetic field changes.

Keywords: Bohm criterion, Kinetic theory, Plasma-wall interaction, Presheath, Sheath.

1. INTRODUCTION

The understanding of plasma sheath is important for various practical applications of plasma as it is enclosed within a fixed volume [1]. The wall is charged up negatively with respect to the core plasma due to the high speed electrons reaching the wall earlier than the ions. Due to this reason,. The negative potential then attracts the ions and repels electrons forming a thin positive space charge region in front of the wall. This positive space charge region, known as the 'sheath' separates the negatively charged wall from the quasineutral 'presheath' plasma. The sheath structure and the overall plasma will be stable only if the ions moving towards the wall satisfy the Bohm criterion [2, 3]. 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 behavior [4, 5].

The plasma sheath is one of the oldest problems in plasma [3, 6] and in recent years, the sheath formed between magnetized plasma and a particle absorbing wall has received a considerable amount of attention [7-11]. 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 [1, 11].

In typical boundary layer problems the sheath region is of several electron-Debye lengths, which is much smaller than the characteristic extension of the plasma. Such a sheath can only be formed, if the Bohm criterion [2, 4] is satisfied which demands that the ions enter the sheath region with a high velocity, which cannot be generated by thermal ion motion alone [4]. In its kinetic form the Bohm criterion in the presence of a magnetic field reads

$$\left\langle \frac{1}{v_{\parallel}^{2}} \right\rangle \le \frac{1}{C_s{}^{2}} \quad \text{......................................} \ (1)$$

where,

$$C_s = \sqrt{\frac{k(\gamma^i T_{PS}^i + \gamma^e T_{PS}^e)}{m^i}}$$

is the ion-acoustic velocity defined at the presheath side of the sheath edge, with k is Boltzmann constant, γ^i and γ^e the ion and electron polytropic constants, respectively, T^i_{ps} and T^e_{ps} the ion and electron temperatures at the presheath side of the sheath edge, respectively and m^i is the mass of ion species [3, 5].

In this work, the velocity variation of ions in a magnetized plasma sheath for different magnitudes of magnetic field at constant obliqueness has been studied. This study is important to observe the particle dynamics change and the particle interaction with the material wall in a magnetized plasma sheath. The kinetic trajectory simulation (KTS) method [12] has been employed to obtain the solution to a non-neutral, collisionless plasma sheath.

2. METHODS AND MODEL

The Boltzmann kinetic equation that describes the particle motion in terms of the velocity distribution function is given as [7]

$$\frac{\partial f}{\partial t} + \vec{v}.\nabla f + \frac{\vec{F}}{m}.\nabla_v f = \left(\frac{df}{dt}\right)_c \text{ ....(2)}$$

where $\vec{F}$ the macroscopic forces that acts on the particles, and $\left(\frac{df}{dt}\right)_c$ is the rate of change of distribution function due to collisions. In the absence of collision equation (2) becomes the well-known Vlasov equation:

$$\frac{\partial f}{\partial t} + \vec{v}.\nabla f + \frac{q}{m}(\vec{E} + \vec{v} \times \vec{B}).\nabla_v f = 0 \text{ ....(3)}$$

This equation is valid in the plasma sheath region as its scale length is much smaller compared to the collision mean free path. In KTS method the Vlasov kinetic equation is solved to study bounded plasmas for given initial and boundary conditions [12-14]. At any point in the phase space, trajectory integration of the kinetic equations yield the respective particle distribution function at that point. As the distribution function is known, the particle density of the species ‘*s*’ is calculated using

$$n^s(\vec{x}) = \int_{-\infty}^{+\infty} d^3v\, f^s(\vec{x}, \vec{v}) \text{..............................(4)}$$

The geometry of the magnetized plasma sheath model for the present case is shown in Fig. 1. The region of interest is bounded by the two parallel planes, at $x = L$ (absorbing wall) and $x = 0$ (the plasma side, i.e., the sheath entrance). The oblique magnetic field lies on the *x*-*y* plane which makes an angle θ with the direction of electric filed such that the magnetic field can be expressed as

$$\vec{B} = B_0(\cos\theta\,\hat{x} + \sin\theta\,\hat{y}) \text{ .... (5)}$$

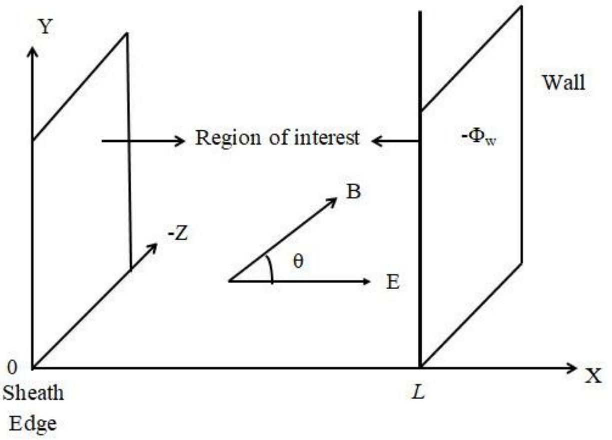

Fig. 1: *Geometry of the plasma sheath model.*

The plasma, consisting of electrons and singly charged ions, enters the simulation region with cut-off Maxwellian velocity distributions; the wall is perfectly absorbing. Thus, the velocity distribution function of electron is,

$$f^e(x,v) = A^e \exp\left[-\left(\frac{v_x^2 + v_y^2 + v_z^2}{v_{tf}^{e^2}}\right) + \frac{e\phi(\vec{x})}{kT_e}\right]\Theta\left[v^e_{cL}(x) - v_x\right]\text{...(6)}$$

where $v^e_c(x) = \sqrt{\frac{2e[\phi(x) - \phi_0]}{m^e}}$ is the cut off velocity of electron at *x*, *k* is the Boltzmann constant and Θ (*x*) is the Heaviside function i.e.,

$\Theta\,(x) = 1$ if $x \geq 0$...................................... (7)

= 0 otherwise.

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

$$f^i(L,v) = A^i \exp\left[-\left(\frac{(v_x - v^i_{mL})^2 + v_y{}^2 + v_z{}^2}{v^i_{tf}{}^2}\right)\right]\ \Theta\left(v^i_{cL} - v_x\right)\text{..(8)}$$

where, $v^s_{tf} = \sqrt{\frac{2kT^s}{m^s}}$ is the thermal velocity of particle species ‘*s*’, v^i_{mL} is the Maxwellian-maximum velocity of ions at $x = L$ and v^i_{cL} ($v^i_{cL} <$ 0) is the cut-off velocity of ions at $x = L$.

Once all the starting parameters at the sheath entrance are known the characteristic equations of motion are solved, for 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. For the velocity distribution given by equation (8), the ion density at any point within the sheath region is given as

$$n^i(x) = A^i \int_{-\infty}^{+\infty} dv_x \int_{-\infty}^{+\infty} dv_y \int_{-\infty}^{+\infty} dv_z \left[-\left(\frac{\left(v_x - v^i_{mL}\right)^2 + v_y^2 + v_z^2}{v^{i^2}_{tf}} \right) \right] \Theta\left(v^i_{cL} - v_x\right) \quad (9)$$

and the electron density is obtained analytically as

$$n^e(\phi) = n^e_L \exp\left[\frac{e\phi(x)}{kT^e_f}\right] \left[\frac{1 + erf\sqrt{\dfrac{e(\phi(x) - \phi_0)}{kT^e_f}}}{1 + erf\sqrt{\dfrac{-e\phi_0}{kT^e_f}}} \right] \quad (10)$$

The calculations are iterated self-consistently unless the resulting potential is stable which is verified by a pre-assigned accuracy parameter in the KTS method [12]. The various components of velocity of ions in the plasma sheath have been computed using Lorentz force equation

$$m^i \frac{d\vec{v}_i}{dt} = q\left[-\vec{x}\frac{\partial\phi}{\partial x} + \left(\vec{v}_i \times \vec{B}\right) \right] \quad ....(11)$$

where q is the charge and $\vec{v}_i$ is the ion velocity, and ϕ is the electrostatic potential.

3. RESULTS AND DISCUSSION

The results obtained by solving the related kinetic equations using the KTS method is presented for hydrogen plasma having temperature of 1 eV at the sheath entrance, where the electron temperature is 10 eV. The simulation region is 10 electron-Debye lengths which is discretized into 41 grid points. The ion velocity profile with time for different values of magnetic field (1.5 mT - 10.5 mT) at fixed obliqueness of 30 ° has been studied.

The temporal dependence of ion velocity for the magnetic field of 1.5 mT is shown in Fig. 2, which shows initially the ions spend more time gyrating. With the time, the frequency as well as amplitude of gyration decreases gradually. The mean values of *x*, *y*, and *z*-components of velocity are -45.21 m/s, 6863 m/s and 11490 m/s, respectively. The *x*, *y* and *z*-components of velocity oscillate with maximum amplitudes of 9839 m/s, 7913 m/s and 4840 m/s, respectively.

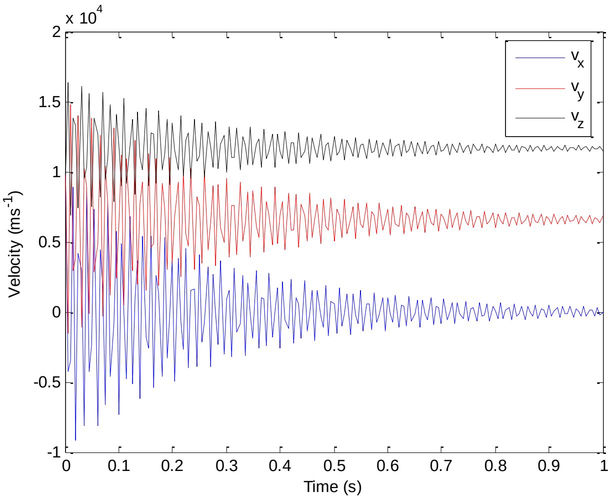

***Fig. 2:** Velocity variation of ions with time for magnetic field 1.5 mT.*

Fig. 3 shows the velocity profile of ions at 4.5 mT magnetic field. The mean values of *x*, *y* and *z*-components of velocity are -0.1347 m/s, 6651 m/s and 11610 m/s, respectively. Compared to the case of 1.5 mT, as the strength of magnetic field increases, it is found that the mean values of *x* and *z* velocity components increased whereas the *y*-component is decreased. The amplitudes of oscillation of velocity is found to be 9794 m/s, 7693 m/s and 4440 m/s, respectively.

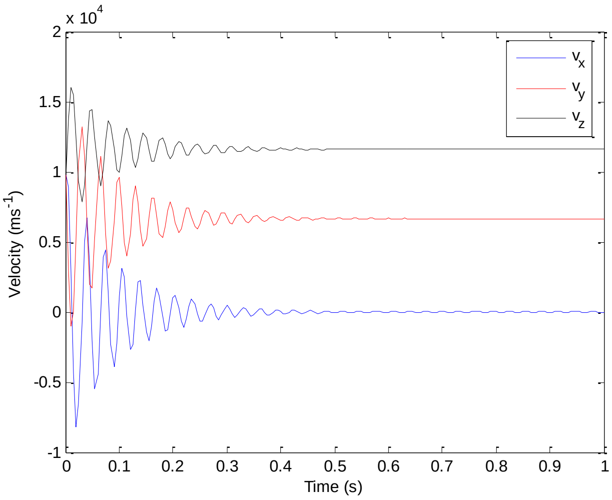

***Fig. 3**: Velocity variation of ions with time for magnetic field 4.5 mT.*

Likewise, at 7.5 mT, the ion velocities are displayed in Fig. 4, in which the mean value of x-component is nearly equal to zero whereas y and z-components are 6666 m/s and 11600 m/s, respectively. However, maximum amplitude of the x-component velocity is the largest with 9794 m/s, compared to 7334 m/s, and 4233 m/s, of y and z-components, respectively. In comparison to 1.5 mT the frequency of oscillation decreases much faster for both 4.5 and 7.5 mT. The oscillation of each component of velocity becomes not significant after 0.5 second (in case of 4.5 mT; Fig. 3), and after 0.3 second (in case 7.5 mT; Fig. 4). Similar nature is shown for the magnetic field strength of 10.5 mT (Fig. 5) where the mean values of x, y and z-components are 10^{-4} m/s, 6673 m/s and 11600 m/s, and the maximum amplitudes of oscillation are 9794 m/s, 6879 m/s and 3970 m/s, respectively.

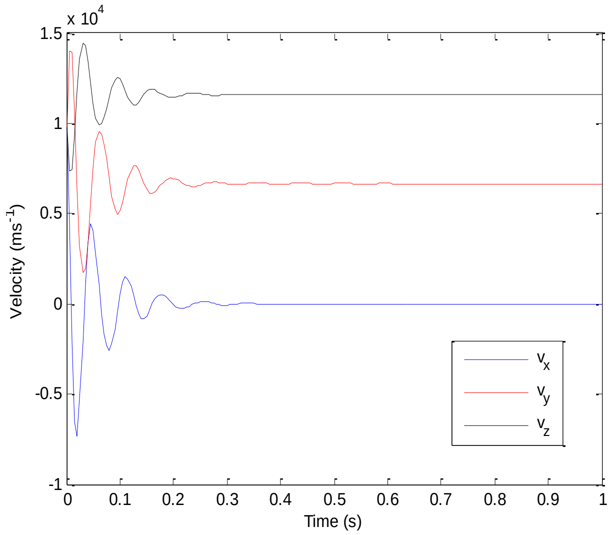

Fig. 4: *Velocity variation of ions with time at magnetic field 7.5 mT.*

The overall variation of mean values of velocity components for different magnetic fields is displayed in Fig. 6. It is found that the mean value of x-component is almost zero, however the mean values of y and z-components differ with the field strength. The y-component of velocity is almost constant around 6660 m/s and the z-component is almost constant around 11600 m/s for the magnetic field beyond 2 mT.

Fig. 7 shows the overall variation of maximum amplitude of velocity components for different varying magnetic field. The maximum amplitude of x-component is constant around 9794 m/s. On the other hand the highest values of the maximum amplitude of y and z-components are around 8100 m/s and 4400 m/s, respectively at magnetic field of 1.5 mT whereas lowest values of the amplitudes are 4489 m/s and 2070 m/s respectively at magnetic field of 6 mT.

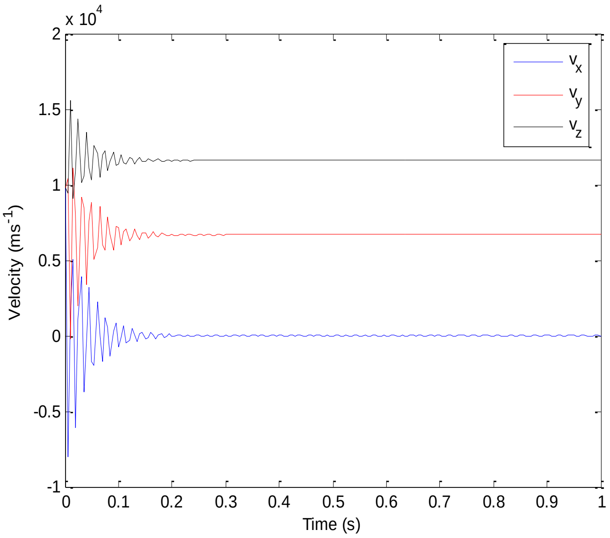

Fig. 5: *Velocity variation of ions with time at magnetic field 10.5 mT.*

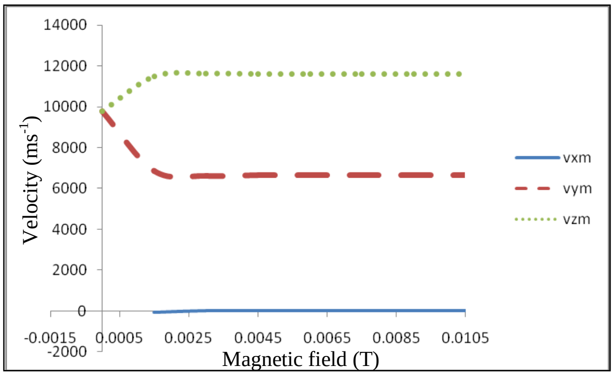

Fig. 6: *Variation of mean value of velocity with respect to magnetic field at angle 30°.*

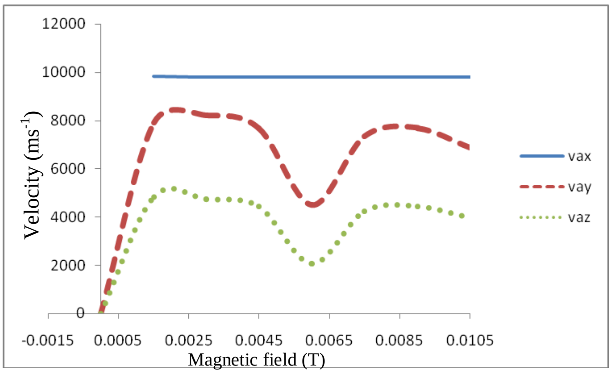

Fig. 7: *Variation of maximum amplitude of velocity with respect to magnetic field at angle 30°.*

4. CONCLUSIONS

The variation of ion velocity in a magnetized plasma sheath for different magnitudes of magnetic field at constant obliqueness has been studied. The mean values as well as the frequency of oscillation of three component of velocity of ions changes

The variation of ion velocity in a magnetized plasma sheath, which consists of a single species of positive ions and electrons, was studied using kinetic theory. The temporal component of ion velocity oscillates and its oscillations as well as amplitudes are highly influenced by the magnetic field. After 0.5 second the oscillation of each component of velocity is negligible for the magnetic field 4.5 mT whereas the oscillation is negligible after 0.3 second for the magnetic field of 7.5 mT. When the magnetic field increases, the mean value of *y*-component decreases and attains 6660 m/s whereas the *z*-component is increased and attains 11600 m/s. The study is useful in understanding the exact particle behavior in magnetized plasma sheath region and can be important in material processing, plasma etching, confinement of plasma in fusion devices, surface treatment, lighting, medicine etc.

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