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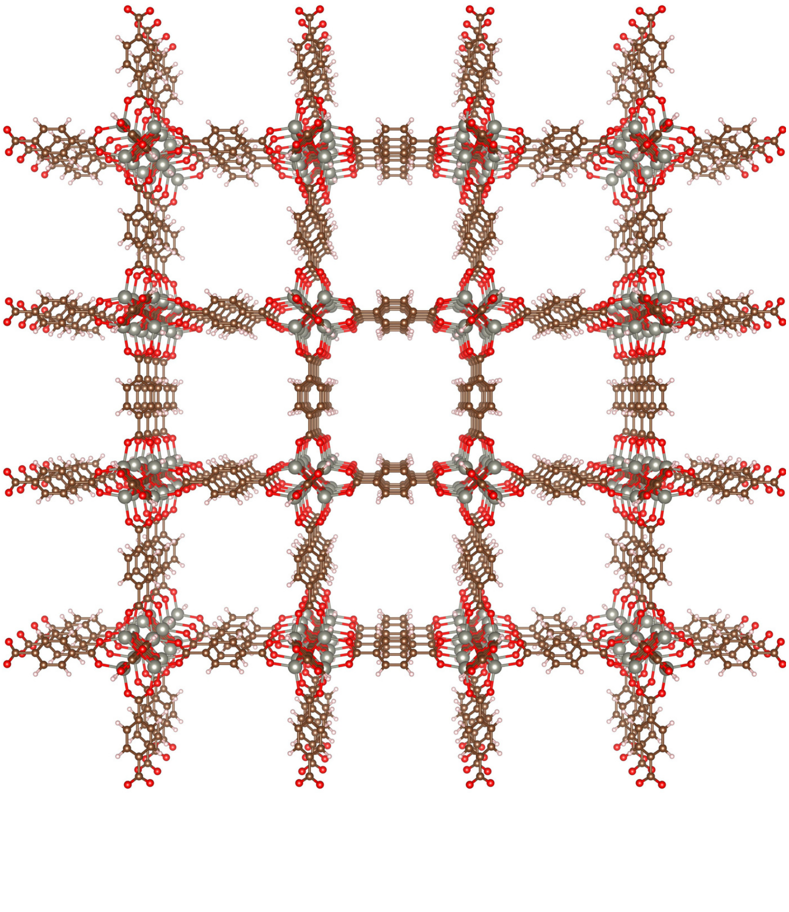

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Cover: Ball-and-stick model of MOF-5. © Roshani Sharma. Printed with permission.

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Himalayan Physics

Mean value and velocity variation of ions in different magnetic field at constant obliqueness

Research Article

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Abstract: The variation of mean values of different components of velocities concerning the magnetic field has been numerically investigated using a kinetic trajectory simulation model at a constant angle and electric field. At an angle of 30°, mean values of different components of velocities at the different magnetic fields have been studied. As the magnetic field changes, the mean values of the three velocity components also change, but as the magnetic field increases from 2.5 mT to 5.5 mT mean value is almost constant.

Keywords: Plasma sheath • Bohm- criterion • Kinetic theory • Magnetic field • Mean value

I. Introduction

Average value variation of different components of velocity of ions for different magnetic fields is a recent field of research in plasma physics [1–4]. Now a day, the sheath formed between magnetic plasma and a particle-absorbing wall has received significant attention [5–10] . As the plasma is confined to any closed surface, plasma interacts with the material surfaces, which is crucial in all plasma applications. Hence, properly understanding this interaction with the material surface is important in all plasma applications [7]. If the plasma–wall interaction is well understood, it will be possible to control heat loading, energy transfer, and particle flow toward the wall and the overall behavior of plasma [3, 4].

Chodura [1] showed that when a magnetic field is applied at some angle to the solid surface, a magnetic pre-sheath appears just before the Debye sheath, producing a significant electric field in this region, deduces a theoretical model for sheath formation, viz., Bohm-Chodura plasma sheath criterion. Then after entering the magnetic pre-sheath, Bohm-Chodura introduced the new condition to the flow velocity of ions constrained to satisfy the Chodura condition [11–14]. The absorbing wall is charged up negatively due to the higher velocity of the plasma electrons. The plasma electrons have much more velocity as compared with that of the ions. Due to this reason, a negative potential is developed in the absorbing wall, which attracts the ions and repels part of the electrons, forming a positive space charge region in front of the wall, which is a 'sheath', which shields the

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quasineutral (bulk) plasma from the negative wall. The plasma wall transition region (PWT) extends from the bulk plasma to the solid surface. To exist in such a sheath, the instreaming ions at the sheath edge must satisfy the Bohm criterion condition. The width of the plasma sheath depends not only on the obliqueness of the field but also on the collision frequencies and the plasma magnetization. As the angle between the magnetic field and the wall increases, then the size of the sheath layer decreases [13].

This study is very important in magnetized plasma sheaths to see the change in particle wall interaction and particle dynamics. Plasma sheath significantly influences the charged particles and the energy flux to the wall, which modifies the absorption, emission of impurities, and all other characteristics in the plasma [7]. The Kinetic Trajectory Simulation (KTS) model [10-13] has been used to obtain a solution to a non-neutral, time-independent, collisionless plasma sheath. Hence, we study the mean value variation of different components of the velocity of ions for different magnetic fields. In an oblique magnetic field, the pre-sheath consists of two distinct regions: collisional and magnetic pre-sheath. The collisional pre-sheath is adjacent to the bulk plasma, where the electron pressure gradient accelerates electrons along magnetic field lines. The magnetic pre-sheath is adjacent to the sheath, where the electric field is powerful to deflect the ions from their motion along the magnetic field [1]. The study is useful in particle behavior in magnetized plasma sheath regions and is important in plasma etching, material processing, surface treatment, medicine, controlled thermonuclear fusion, agriculture, and many more.

This paper is organized as follows: In section 2, we discuss the basic principle of the KTS method in a simplified form. In this section, we explain the distribution function in the collisionless case. In section 3, we discuss our magnetized plasma sheath model. In this section, we apply the Lorentz force equation, solved by the Runge-Kutta method in MATLAB using boundary conditions. In section 4, we obtain the result in graphical form, discuss our result, and summarize our work. Finally, in section 5, we conclude our work.

II. Basic Principle of KTS Method

For numerically calculating self-consistent, time-independent kinetic plasma states in some given bounded spatial region KTS method is used, whose characteristic feature is that the particle species' distribution functions are calculated by solving the related (collisionless) or collisional) kinetic equations along the respective collisionless particle trajectories.

The fundamental equation which $f(\vec{r},\vec{v},t)$ has to satisfy is the Boltzmann equation [9].

$$\frac{\partial f}{\partial t} + \vec{v}\cdot\nabla f + \frac{\vec{F}}{m}\cdot\nabla_v f = \left(\frac{df}{dt}\right)_c \tag{1}$$

Where $\vec{F}$ is the force acting on the particles, and $\left(\frac{df}{dt}\right)_c$ is the time rate of change of f due to collisions. The symbol ∇ stands for the gradient in (x, y, z) space. The symbol represents the gradient in velocity space, and $f(\vec{r},\vec{v},t)$ is a velocity distribution function. In collisionless cases the equation is called the Vlasox equation

$$\frac{\partial f}{\partial t} + \vec{v}\cdot\nabla f + \frac{q}{m}(\vec{E}+\vec{v}\times\vec{B})\cdot\nabla_v f = 0 \tag{2}$$

The distribution function at every point along the trajectory can be obtained if its value at one point is known. Then the number density of particle species s is given by

$$n^s(\vec{x}) = \int_{-\infty}^{+\infty} d^3v f^s(\vec{x}, \vec{v}) \quad (s = e, i) \tag{3}$$

The electric space charge density is defined as

$$\rho(\vec{x}) = \sum_s q^s n^s(\vec{x}) \tag{4}$$

The electric field is given as

$$\vec{E}(\vec{x}) = -\nabla\phi(\vec{x}) \tag{5}$$

And the electrostatic potential is to be found in Poisson's equation

$$\nabla^2\phi(x) = -\frac{\rho(\vec{x})}{\varepsilon_0} \tag{6}$$

In the KTS method, we solve the kinetic equation and other basic equations describing the plasma for a given boundary and initial conditions.

III. The Plasma Sheath Model

The 1d3v model of the magnetized plasma sheath is shown schematically in Fig. 1.

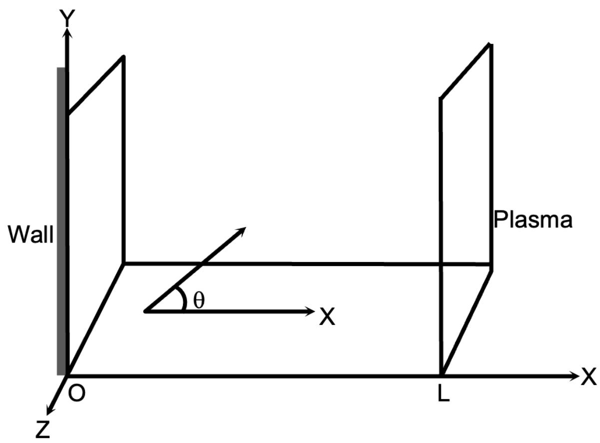

Figure 1. Diagram of the plasma sheath model

The simulation region should be bounded by two parallel planes at x = 0 and x = L. These two parallel planes have specified x = L as the "plasma entrance," and an absorbing wall is specified by x = 0. We assume the angle between the oblique magnetic field along the x-axis or electric field to be θ. The simulation region having two boundaries is perfectly absorbing and does not emit any particles. Consider the plasma particles entering the simulation region from the plasma entrance wall with cut-off Maxwellian velocity distribution functions. Accordingly, the electron velocity distribution function is given by,

$$f^e(x,v) = A^e \exp\left[-\left(\frac{v_x^2+v_y^2+v_z^2}{v_t^{e2}}\right)+\frac{e\phi(x)}{kT^e}\right]\Theta\left[v_c^e(x)-v_x\right] \tag{7}$$

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

$$\begin{aligned}\theta(x) &= 1 \text{ if } x \geq 0 \\ &= 0 \text{ otherwise.}\end{aligned} \tag{8}$$

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

$$f^i(L,v) = A^i \exp\left[-\left(\frac{\left(v_x - v_{mL}^i\right)^2+v_y^2+v_z^2}{v_t^{i2}}\right)\right]\Theta\left(v_{cL}^i - v_x\right) \tag{9}$$

where $v_t^s = \sqrt{\frac{2kT^s}{m^s}}$ is the species-s (ion and electron) thermal velocity, v_{mL}^i is the ion "Maxwellianmaximum" velocity at $x = L$ and v_{cl}^i $\left(v_{cl}^i < 0\right)$ is the ion cut off velocity at $x = L$. 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 to become shifted Maxwellian as given by Equation 9.

The various components of the velocity of ions have been computed by Lorentz force equation

$$m\frac{d\vec{v}}{dt} = q(\vec{v}\times\vec{B}) + q\vec{E} \tag{10}$$

IV. Results and Discussion

The variation of mean values of different components of velocities with respect to the magnetic field (0.5 mT, 1 mT, 1.5 mT, 2 mT, 2.5 mT, 3 mT, 3.5 mT, 4 mT, 4.5 mT, 5 mT, and 5.5 mT) have been calculated for obliqueness of the field 30°. The results of the calculation are shown in Figs. 2 and 3. Fig. 2(a) shows that at a magnetic field of 0.5 mT, the mean value of the x-component of velocity is maximum, i.e., 8282 m/s. Increasing the magnetic field to 1mT mean value rapidly decreases to 818 m/s. When the magnetic field is further increased to 1.5 mT, the mean value decreases and becomes negative i.e, -79.12 m/s. At 2 mT, the mean value slightly increases to -44.27 m/s. After 2.5 mT, mean values remain almost constant.

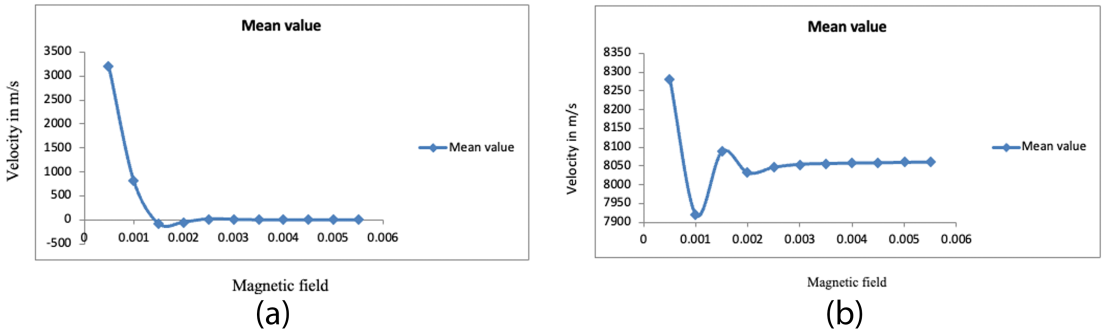

Figure 2. Variation of the mean value of velocity's components (a) X and (b) Y, with respect to the magnetic field and at angle 30 °

Fig. 2(b) shows that at the same value of magnetic field 0.5 mT, the mean value of the y-component of velocity is maximum i.e 8282 m/s. Increasing the magnetic field to 1 mT mean value decreases to 7919 m/s. When the magnetic field is further increased to 1.5 mT mean value slightly increases to 8088 m/s, whereas at 2 mT mean value slightly decreases to 8031 m/s. After 2.5 mT mean value almost remains constant.

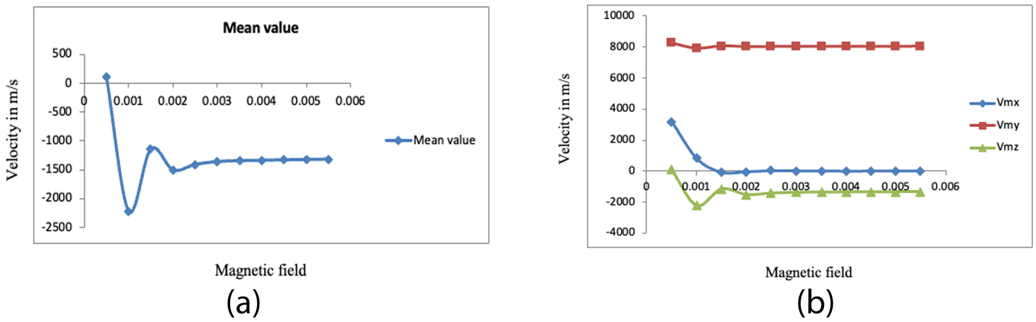

Figure 3. Variation of the mean value of (a) Z and (b) Overall, velocity component with respect to the magnetic field and angle 30 °.

Similarly, Fig. 3(a) shows that at the same magnetic field value, 0.5 mT mean value of the z-component of velocity is maximum i.e 109.1 m/s. On increasing the magnetic field to 1 mT mean value rapidly decreases and becomes negative, which is -2216 m/s. When the magnetic field is further increased to 1.5 mT, the mean value starts increasing instead of decreasing, which becomes -1134 m/s. At 2 mT mean value slightly increases to -1501 m/s. After 2.5 mT mean value remains almost constant.

In summary, Fig. 3(b) shows the overall variation of mean values of different components of velocities with respect to different magnetic fields. In this figure, among the minima, the lowest value of the mean value of the x-component of velocity is around -79.12 m/s at a magnetic field of 1.5 mT. In contrast, the maximum value is around 3209 m/s at a magnetic field of 0.5 mT. On the other hand, the minimum and the maximum value of the mean value of the y-component of velocity is around 7919 m/s and 8282 m/s at magnetic fields of 1 mT and 0.5 mT, respectively. Similarly, for the z-component, the smallest and largest value of the mean velocity value is

-2216 m/s and 109.1 m/s at magnetic fields of 1 mT and 0.5 mT, respectively. This figure also shows that the mean value is almost constant after the magnetic field of 2.5 mT in each velocity component at an angle of 30 °.

V. Conclusions

The magnetized plasma sheath has been studied using the KTS method, and a scheme of mean value variation has been developed for the magnetized plasma sheath. At different magnetic fields, as the obliqueness of the field is constant, the separation of the mean values and the maximum amplitude of all three velocity components also changes. At a constant angle 30°, mean values of different velocities components at different magnetic fields have been observed. It is also observed that as the magnetic field changes, the mean values of three component of the velocities also changes, but as the magnetic field is increased from 2.5 mT to 5.5 mT mean value is almost constant. Our work is important in fields like fusion devices, agriculture, cancer treatment, teeth treatment, etc. This study helps develop and evaluate the solution of the pre-sheath – sheath coupling problem. This is also helpful in extending the 1d1v KTS model to 1d3v and the 3d3v model.

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