Plasma Wake and Interaction force for Diatomic Molecular ion Transporting through plasmas

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Abstract. The objective of the present work is to study the interactive

potential and forces for a diatomic molecular ion in plasma within the dielectric response theory. The results show that the interactive force shows the asymmetric property due to the wake effects. In addition, the force can be divided into two parts, one is the coulomb force and the other is polarization force. Coulomb force is symmetric, while the polarization force made the main contribution to the asymmetric.

Introduction

The problem of interactions of fast ion beams with matter has been the subject of increasing interest during the past several decades due to its importance in material surface modifications and the inertial confinement fusion (ICF)[1]. Interaction potential and forces are the basic quantities for the study for such an interaction process. In particular, for ion in plasmas, several theoretical models have been built, such as the linear Vlasov-Poisson theory[2,3,4], the binary collision theory[5], and the nonlinear Vlasov-Poisson theory[6,7].

In this paper, we adopt the linearized Vlasov Poisson theory to study the interaction potential and forces for ion moving in plasmas. The aim is to discuss influences of different projectile velocity on the potential and interaction forces. The paper is organized as follows: in Section II the theoretical model is presented. And then, we discussed the simulation results of polarization potential and total potential and the components of forces in x and z direction in Section III. Finally, a short summary is given in Sec. IV.

Theoretical model

Let us first consider a point ion with the charge number Z_1 which moves at the velocity v_p through a plasma target, characterized by the density n_0 and the electron temperature T_e . The charge density of the projectile is

$$\rho_{ext}(\vec{r}, t) = Z_1 e \delta(\vec{r} - \vec{v}_p t) - e \rho_e(\vec{r} - \vec{v} t) \quad (1)$$

Assuming that the projectile velocity is far greater than the ion thermal velocity in the plasma, it follows that only the contributions from the electron component of the plasma will be relevant in the following. The total scalar potential $\Phi(\vec{r}, t)$ in plasma due to the presence of the ion can be determined from the linearized Vlasov-Poisson equations

$$\left(\frac{\partial}{\partial t} + \vec{v} \cdot \frac{\partial}{\partial \vec{r}} \right) f_1(\vec{r}, \vec{v}, t) = - \frac{e}{m_e} \frac{\partial \Phi}{\partial \vec{r}} \cdot \frac{\partial f_0(\vec{v})}{\partial \vec{v}} \quad (2)$$

$$\nabla^2 \Phi(\vec{r}, t) = 4\pi \left[e \int d\vec{v} f_1(\vec{r}, \vec{v}, t) - \rho_{ext}(\vec{r}, t) \right] \quad (3)$$

where m_e is the electron mass, f_1 is the perturbed electron distribution function, and f_0 is the unperturbed electron distribution function which is taken to be Maxwellian. Upon solving Eqs. (2) and (3) by means of the space-time Fourier transform, we obtain

$$\Phi(\vec{r}, t) = \frac{1}{2\pi^2} \int \frac{d^3k}{k^2} \frac{\rho_\eta(k)}{\varepsilon(k, \vec{k} \cdot \vec{v}_p)} \exp[i\vec{k} \cdot (\vec{r} - \vec{v}_p t)] \quad (4)$$

showing that the potential $\Phi(\vec{r}, t)$ is stationary in the frame of reference moving with the ion.

$\rho_\eta(k) = Z_1 e \left(1 - \frac{\eta}{1 + (k\Lambda)^2} \right)$ is the charge for heavy ion. In Eq. (4), $\varepsilon(k, \omega)$ is the longitudinal dielectric function of the classical electron plasma, and the expression is as follows:

$$\varepsilon(k, \omega) = 1 + (k\lambda_D)^{-2} [X(\omega/kv_T) + iY(\omega/kv_T)] \quad (5)$$

where $X(\zeta) = 1 - 2\zeta e^{-\zeta^2} \int_0^\zeta e^{t^2} dt$, $Y(\zeta) = \sqrt{\pi} \zeta e^{-\zeta^2}$. So we can write the potential as follows:

$$U(v_p) = \frac{1}{\pi v} \int_0^{k_{\max}} \rho_\eta(k) \frac{dk}{k} \int_0^{kv_p} d\omega \operatorname{Re} \left[\frac{1}{\varepsilon(k, \omega)} \right] \quad (6)$$

For a diatomic ion, we can get the expression of interaction potential as follows based on the Eq. (4).

$$\begin{aligned} U(\vec{r}_{12}) &= \int d\vec{r}' \rho_{\text{ext}}(\vec{r}' - \vec{r}_{12}, t) \Phi(\vec{r}', t) \\ &= \frac{(Z_1 e)^2}{2\pi^2} \int \frac{d^3k}{k^2} \frac{1}{\varepsilon(k, \vec{k} \cdot \vec{v}_p)} e^{i\vec{k} \cdot \vec{r}_{12}} \end{aligned} \quad (7)$$

Where $\vec{r}_{12} = \vec{r}_1 - \vec{r}_2$ is the relative position of the ion in cluster. Let us consider the cluster is in the direction of z, and we can get $\vec{r}_{12} = \{\rho, z, \phi\}$ in the cylindrical coordinate system.

$$\begin{aligned} U(\rho, z) &= \frac{2(Z_1 e)^2}{\pi v} \int_0^{k_{\max}} \frac{dk}{k} \int_0^{kv_p} d\omega J_0(\rho \sqrt{k^2 - \omega^2/v_p^2}) \\ &\quad \times \left\{ \cos\left(\frac{\omega z}{v_p}\right) \operatorname{Re} \left[\frac{1}{\varepsilon(k, \omega)} \right] - \sin\left(\frac{\omega z}{v_p}\right) \operatorname{Im} \left[\frac{1}{\varepsilon(k, \omega)} \right] \right\} \end{aligned} \quad (8)$$

where, $r_{12} = \sqrt{\rho^2 + z^2}$, and $J_0(x)$ is the zeroth Bessel function.

In order to simplify the notation, we introduce dimensionless variables $v = v_p/v_T$, $\tau = k\lambda_D$ and $\zeta = \omega/kv_T$, so that the interaction potential is finally expressed as

$$U(\rho, z) = U_c(\rho, z) + U_p(\rho, z)$$

$U_c(\rho, z) = (Z_1 e)^2 / r_{12}$ is the Coulomb potential and $U_p(\rho, z)$ is the polarization potential.

$$\begin{aligned} U_p(\rho, z) &= \frac{2(Z_1 e)^2}{\pi \lambda_D} \frac{v_T}{v_p} \int_0^{\tau_{\max}} d\tau \int_0^{v_p/v_T} d\zeta J_0(\rho \tau \sqrt{1 - (v_T \zeta / v_p)^2}) \\ &\quad \times \left[\cos\left(\frac{v_T}{v_z} \frac{z}{\lambda_D} \tau \zeta\right) G_r(\tau, \zeta) - \sin\left(\frac{v_T}{v_z} \frac{z}{\lambda_D} \tau \zeta\right) G_i(\tau, \zeta) \right] \end{aligned} \quad (9)$$

where

$$G_r(\tau, \zeta) = \frac{X(\zeta)[\tau^2 + X(\zeta)] - Y^2(\zeta)}{[\tau^2 + X(\zeta)]^2 + Y^2(\zeta)}, \quad G_i(\tau, \zeta) = -\frac{\tau^2 Y(\zeta)}{[\tau^2 + X(\zeta)]^2 + Y^2(\zeta)}$$

Results and discussion

Figure 1 (a)-(b) show the polarized potential and total potential for a diatomic molecular ion moving through a plasma target with $n_0 = 10^{20} \text{ cm}^{-3}$ and $T_e = 10^2 \text{ eV}$ on the longitudinal distance z/λ_D at fixed radial distance $\rho = \lambda_D$, for different speeds v_p . One can see that the dependence of the potential

on the coordinate z is rather asymmetric, especially for polarized part. The reason is the consequence of the wake-like oscillatory spatial pattern of the medium response. In particular, the wavelength of the oscillations behind the projectile appears to be of the order of $2\pi v_p/\omega_p$, where $\omega_p=v_T/\lambda_D$ is the electron plasma frequency, in analogy to the wakes in solid targets [8]. When the projectile velocity is higher, and the oscillation amplitude is much more obvious.

Figs. 2 (a) and (b) show, respectively, the dependence of the longitudinal, F_z , and the transversal, F_x , components of the total interaction force between the two ions on the longitudinal distance z/λ_D , with fixed transversal distance $\rho=\lambda_D$, for the same set of parameters as in Fig. 1.

Figure 1. The polarized potential and total interaction potential as a function of the longitudinal distance z/λ_D for a diatomic ion cluster with velocities $v_p = v_T, 2v_T$, and $3v_T$, moving at the transversal distance $\rho=\lambda_D$ through a plasma with $n_0=10^{20} \text{ cm}^{-3}$ and $Te=10^2 \text{ eV}$. Here, $U_0 = (Z_1 e)^2/\lambda_D$.

Figure 2. The component of the total interaction force (a) the longitudinal, F_z , and (b) the transversal, F_x , on the longitudinal distance z/λ_D for a diatomic ion cluster with velocities $v_p = v_T, 2v_T$, and $3v_T$, moving at the transversal distance $\rho=\lambda_D$ through a plasma with $n_0=10^{20} \text{ cm}^{-3}$ and $Te=10^2 \text{ eV}$. Here, $F_0 = (Z_1 e)^2/\lambda_D^2$.

Summary

We use the molecular dynamic simulation method to study the interaction between a diatomic ion and a plasma target. Using the classic dielectric function, the expressions of potential and interaction force are derived. Simulation results show that the dependence of the potential on the coordinate z is rather asymmetric due to the consequence of the wake-like oscillatory spatial pattern of the medium response. The oscillation amplitude increases with the projectile velocity both for potential and interaction force due to the excitation of wake effects in plasmas.

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