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Influences of finite Larmor radius on wake effects and stopping power for proton moving in magnetized two-component plasma

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ABSTRACT

Considering finite Larmor radius (FLR) effects, wake effects and stopping power induced by proton projectile in two-component magnetized plasma are investigated within a linear response framework. Numerical results show that, FLR lessens wake effects and stopping power, essentially through excitation of collective plasma electron modes.

1. Introduction

The energy loss of charged particles in plasmas has been a great interesting topic due to its considerable importance for the study of inertial confinement fusion (ICF) driven by heavy-ion beams [1–3] and fast ignition [4,5], and magnetic confinement fusion (MCF) heated by neutral beam injection (NBI) [6–8]. Especially, while NBI as application to heating, current drive and rotation drive [9] was successfully proved in tokamaks, it has become a further concern.

To describe energy loss of charged particles in a plasma, there are two standard analytical approaches [10–12], the dielectric linear response (LR) and the binary collision (BC) model, which are complementary to each other. In LR model, considering the ion as a perturbation of the target plasma, the energy loss is caused by the interactions between the projectile and surrounding polarizing plasma particles. And the stopping requires a cutoff at small distances, where hard collisions between the ion and electrons cannot be treated any more as a weak perturbation. In BC approximation, on the other hand, the stopping, taking place in successive binary collisions between the charged particles and plasma particles, also requires cutoff parameters at large distances to account for screening. In the absence of a magnetic field, both approaches give the same results, if physically reasonable cutoffs are used in the Coulomb logarithms [13,14]. However, the presence of a magnetic field introduces complications. Besides, there are numerical simulations to check the results of the above two approaches, such as particle-in-cell (PIC) and molecular dynamic (MD) simulation [10].

Since magnetic fields are experimentally available in the MCF and electron cooling processes, many theoretical calculations of the stopping power in a magnetized plasma have been presented [12, 15–24]. When a charged particle penetrates into a magnetic field, it suffers the Lorentz force only in the direction across the magnetic field. The magnetic field suppresses the momentum transfer in the transverse direction, but enhances the longitudinal momentum transfer. It is found that the magnetic field reduces the energy loss for ion motion parallel to the magnetic field while it enhances the energy loss for transverse ion motion [16,17]. In Ref. [18], the energy loss rate for arbitrary test particle velocities in the limit of sufficiently strong magnetic field was calculated, which was much higher than that without magnetic field. Besides, it is also found that the magnetic field reduces the stopping power at high particle velocities, while enhances the stopping power at low particle velocities [19].

As we all know, most of the theoretical studies on energy losses in magnetized plasmas only take into account the dynamic polarization of electrons, while neglecting that of ions. These results are valid if the ratio between the test particle velocity and plasma electron thermal velocity satisfies $u/v_{Te} > (m_e/m_i)^{1/3}$ (here, m_e, m_i are the masses of electron and ion, respectively) [25]. Actually, without an external magnetic field, the contribution of plasma ions on the stopping is relatively small compared to that of the electrons [1]. However, with an increasing magnetic field the electrons move along the field lines just like beads on a wire, with no energy loss at all for $\mathbf{u} \parallel \mathbf{B}_0$ in the limit $\mathbf{B}_0 \to \infty$, except for possible col-

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lective effects [17]; at the same time, the energy losses of plasma ions get larger due to the dynamic polarization of the ions enhanced with the magnetic field increased, which is documented in Ref. [20]. The authors also found that, in a strong magnetic field, the ion stopping contributes mainly to the energy loss for low incidence velocity $u/v_{Te} < 1$, while electrons stopping for high incidence velocity becomes dominant in weak magnetic fields [20].

However, to our best knowledge, only a few theoretical studies on energy losses consider the Larmor rotation of the projectile, and pay special attention to the case of extreme magnetization, as well as to the incidence velocity paralleled the magnetic field [18,21]. In Ref. [22], the stopping power involved the cyclotron motion of the test particle has been detailedly performed with arbitrary orientation between the projectile velocity and magnetic field, which decreases strongly as the angle varies from 0 to $\pi/2$. Nevertheless, the authors only took the dynamics polarization of plasma electrons. And the projectile velocity here is so high that influences of finite Larmor radius (FLR) are unconspicuous. In Refs. [23,24], the stopping of an ion projectile at low velocity in a strong magnetic field is investigated within a full hydrodynamic treatment including FLR effects in target ions. For a high velocity incident particle, the energy loss is mainly due to collisions with plasma electrons. When the particle slows down, the collisions with ions become more important. Many experiments show that, in the present generation of tokamaks, neutral beams predominantly heat ions [26]. The plasma ions can respond thoroughly to the perturbation of the projectiles while electrons are restricted by the strong magnetic field due to $m_i \gg m_e$. Therefore, one expects that for the low velocity projectile in helical movements around magnetic field lines, the dynamic polarization of ions may bring a considerable influence on the energy loss.

In this work, a linearized dielectric theory is put forward to calculate the wake effects and energy loss of charged particle in magnetized two-component plasma, especially considering FLR effects of the projectile. The comparisons of the induced potential, perturbed density of the electrons and stopping power for cases with and without FLR effects for different parameters, such as the magnetic field, plasma parameters, are presented. We concentrate our attention on the wake field and stopping power in the regions of low particle velocity and strong magnetic field, and try to give the importance of FLR effects on them, especially for the plasma ions. The Letter is organized as follows. In Section 2, taking into account the helical movement of the test particle, the linearized dielectric theory is used to obtain general expressions of the induced potential, perturbed density of the electrons and stopping power. In Section 3, numerical results are discussed to analyze influences of FLR on the wake effects and stopping power. Finally, we offer short conclusions in Section 4.

2. Theoretical model

A schematic diagram is shown in Fig. 1. The plasma under consideration with an electron component and ion component is subject to an external constant magnetic field $\mathbf{B}_0$, which is parallel to z axis. A test particle with charge Ze and velocity $\mathbf{u}$ moves in the magnetized plasma with density n_0 and angle θ with respect to $\mathbf{B}_0$. Taking the helical movement of the test particle into account, the charge density is given by the following expression:

$$\rho_{ext}(\mathbf{r},t) = Ze\delta(\mathbf{r}-\mathbf{R}), \tag{1}$$

with the position of the test particle

$$\mathbf{R} = \delta\big[x - a\cos(\omega_c t)\big]\delta\big[y - a\sin(\omega_c t)\big]\delta(z - u_\parallel t).$$

Here, $\omega_c = ZeB_0/M$, $a = u_\perp/\omega_c$ and M are the cyclotron frequency, the Larmor radius and the mass of the test particle, respectively. $u_\parallel = u\cos\theta$ and $u_\perp = u\sin\theta$ are the particle velocity component along and across $\mathbf{B}_0$ (without specially indicating, the subscripts $\parallel$ and $\perp$ denote the component along and across $\mathbf{B}_0$).

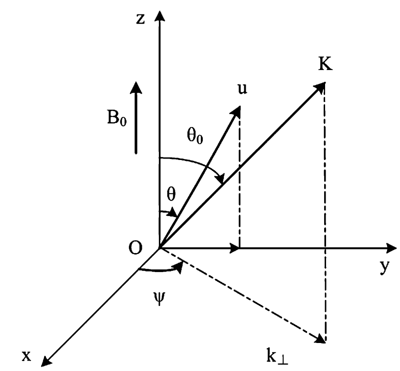

Fig. 1. Geometry of the vectors involved in this Letter.

The linearized Vlasov equation of the electron–ion plasma may be written as

$$\frac{\partial f_{\sigma 1}}{\partial t} + \mathbf{v}\cdot\frac{\partial f_{\sigma 1}}{\partial \mathbf{r}} + \omega_{c\sigma}(\mathbf{v}\times\mathbf{b}_0)\cdot\frac{\partial f_{\sigma 1}}{\partial \mathbf{v}} = \frac{q_\sigma}{m_\sigma}\frac{\partial\phi}{\partial\mathbf{r}}\cdot\frac{\partial f_{\sigma 0}}{\partial\mathbf{v}}, \tag{2}$$

where $f_\sigma = f_{\sigma 0} + f_{\sigma 1}$, with $f_{\sigma 0}$ the unperturbed distribution function and $f_{\sigma 1}$ the first order perturbation of σ species. The subscript $\sigma = e, i$ represents the plasma electron or plasma ion. $\mathbf{b}_0$ is the unit vector paralleled to $\mathbf{B}_0$. q_σ, m_σ and $\omega_{c\sigma} = q_\sigma \mathbf{B}_0/m_\sigma$ denote the charge, mass and cyclotron frequency of σ species, respectively. And, the self-consistent electrostatic potential ϕ is determined by Poisson's equation

$$\varepsilon_0\nabla^2\phi = -\rho_{ext}(\mathbf{r},t) - \sum_\sigma q_\sigma \int d\mathbf{v}\, f_{\sigma 1}(\mathbf{r},\mathbf{v},t). \tag{3}$$

Assuming that each species in a state of equilibrium obeys the Maxwellian distribution

$$f_{\sigma 0}(\mathbf{v}) = \frac{n_{\sigma 0}}{(2\pi v_{T_\sigma}^2)^{3/2}}\exp\left(-\frac{v^2}{2v_{T_\sigma}^2}\right). \tag{4}$$

Here, $v_{T_\sigma} = \sqrt{k_B T_\sigma/m_\sigma}$ is the thermal speed. And T_σ, $n_{\sigma 0}$ are the temperature and the unperturbed density of the σ species, respectively.

Performing the space–time Fourier transform on Eq. (1) through

$$e^{-ik_\perp a\cos(\psi-\omega_c t)} = \sum_{n=-\infty}^{\infty}(-i)^n J_n(k_\perp a)e^{in(\psi-\omega_c t)},$$

one gets

$$\rho_{ext}(\mathbf{k},\omega) = 2\pi Ze\sum_{n=-\infty}^{\infty}(-i)^n J_n(k_\perp a)e^{in\psi}\delta(\omega - n\omega_c - k_\parallel u_\parallel), \tag{5}$$

where $\mathbf{k} = \{k_x, k_y, k_z\} = \{k_\perp\cos\psi, k_\perp\sin\psi, k_\parallel\}$ is the vector, and ψ is the angle between $k_\perp$ and x axis.

By solving Eqs. (2)–(5), the induced potential is obtained as

$$\phi_{ind}(\mathbf{k},\omega) = \phi_{ext}(\mathbf{k},\omega)\big[1 - \varepsilon^{-1}(\mathbf{k},\omega)\big], \tag{6}$$

where $\phi_{ext}(\mathbf{k},\omega) = \rho_{ext}(\mathbf{k},\omega)/\varepsilon_0 k^2$, $\varepsilon(\mathbf{k},\omega)$ is the dielectric function of the homogeneous magnetized two-component plasma, which may be written in the form as

$$\varepsilon(\mathbf{k},\omega) = 1 + \sum_\sigma\left(\frac{k_{D\sigma}}{k}\right)^2\left\{1 + \sum_n\frac{\omega}{\omega - n\omega_{c\sigma}} \times\big[W(\varsigma_n) - 1\big]\Lambda_n(\lambda_\sigma)\right\}, \tag{7}$$