The ponderomotive force of a high frequency field acting on an isotropic plasma

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Recibido el 20 de marzo de 1998; aceptado el 12 de diciembre de 1998

Using the hydrodynamic approach to describe a plasma, an expression for the ponderomotive force of a high frequency field acting on an isotropic plasma is obtained and shown in a simple way. Non stationary terms and the effective collision frequency between particles are taken into account. The collisionless approximation is analyzed.

Keywords: Ponderomotive force; isotropic plasma

Usando el modelo hidrodinámico para describir un plasma, se muestra en forma simple la obtención de una expresión para la fuerza ponderomotriz de un campo de alta frecuencia que actúa sobre un plasma isótropo incluyendo términos no estacionarios y una frecuencia efectiva de colisiones. Se analiza el límite no colisional.

Descriptores: Fuerza ponderomotriz; plasma isótropo

PACS: 52.35.Mw

1. Introduction

Two non-linear mechanisms, excluding non-linear wave interactions, responsible of high frequency (HF) field momentum and energy transfer to the plasma particles can be classified. The first one consists in the transfer of momentum $\mathbf{p} = \hbar\mathbf{k}$ and energy $W = \hbar\omega$ by a mechanism related to the inhomogeneity of the HF field amplitude. Here, $\mathbf{k}$, ω and $\hbar$ are the wave vector, the frequency, and the Planck constant divided by 2π, respectively. It is known that a time averaged force [1, 2]

$$\langle \mathbf{f}_{0\alpha} \rangle = \frac{e_\alpha^2}{4m_\alpha \omega^2} \nabla |\mathbf{E}_0|^2, \tag{1}$$

acts on plasma particles, where e_α and m_α are the charge and mass of the particles, respectively. $\mathbf{E}_0$ is the HF field amplitude.

At this point it is important to specify two concepts used in this work: the valid frequency range of the method used and the validity of the assumed linear relation between the current and the HF electric field. The approximation of a HF field assumed in our theory is: the oscillation frequency ω of the electromagnetic field is large compared with the Larmor (cyclotron) frequency $\Omega = eB/m_e c$ and with the reciprocal transit time v/L, where v is the particle velocity and L is the characteristic length of the device [3]. In the collisional case, it can be imposed the additional condition $\omega \gg \nu$, where ν is the effective collision frequency between particles. There exist several applications, where the study of the motion of charged particles in a HF fields is important as found in focusing and trapping of particles, for example. These processes mean that particles are elastically bound to an axis or a coordinate in space if a binding force acts on them increasing linearly with distance r, *i.e.*, $F = -cr$, where c is a constant [4]. In practice, focusing is obtained using a parabolic potential of the form $\Phi \approx (\alpha x^2 + \beta y^2 + \gamma z^2)$, in cartesian coordinates [3, 4]. The components, along the x, y and z directions, of the equation of motion of the particles moving in a parabolic potential as above can be written in terms of the Mathieu equations [1,4]. The analysis of the coefficients of the Mathieu equations determines both the stable regions (focusing and trapping) and the instable regions (acceleration) of particle motion respectively [5]. A particular case of particle motion in a parabolic potential is the 2-dimensional quadrupole spectroscopy where the focusing of particles is realized using a HF electric field [4]. In these devices, the most relevant frequency region occurs when $\omega > (1/r_0)\sqrt{2eV/m}$, where V is the HF voltage applied and r_0 is the half-distance between electrodes. To achieve a strong focusing (trapping) of particles (3-dimensional quadrupole field), is recommended [6] to use rotating magnetic fields [3, 7, 8] where, the frequency of rotation ω is comparable with the Larmor frequency. Another area of application of HF fields is found in wave guides and resonators theory [5]. If $\omega \ll \omega_{Le}$ - where $\omega_{Le} = 4\pi n_e e^2/m_e$ is the electron plasma frequency, within the framework of the linear theory—the HF field can be introduced as far as the skin penetration depth and the approximation of the ponderomotive force is no longer valid.

The assumption of a linear relation between the HF field and the current is valid when the influence of the HF field on the plasma is small. In an isotropic plasma, this condition is expressed as $E_0 \ll E_c$ [9], where

$$E_c = \frac{\omega_{Le}}{ck} \frac{E_p}{2^{3/2}}.$$

Here $k = \omega/c$ and $E_p = 3T_e m_e \omega^2/e^2$. T_e is the electron temperature and m_e is the electron mass. In the opposite case, for a large-amplitude HF field ($E_0 \gg E_c$), we cross into the region of non linear interaction of a HF field with a plasma where the interaction between waves becomes important. One of the most interesting processes of the non-linear interaction of waves is the parametric resonance. This process is related to the action of a strong (large-amplitude) HF field inducing a strong periodic time variation of the plasma parameters. These fluctuations, in conjunction with the externally imposed HF field can resonantly couple (parametric resonance). When the plasma parameters oscillations become sufficiently strong, some plasma mode is driven unstable by the externally imposed HF field at a different frequency (parametric instability). Parametric instabilities of this kind have been investigated intensively in relation to the laser-plasma interactions [10].

To show the influence of the force on a plasma, it will be considered the force (1) per unit volume of plasma (practically on electrons),

$$\langle \mathbf{f} \rangle = N_\alpha \langle \mathbf{f}_{0\alpha} \rangle = -\frac{\omega_{L\alpha}^2}{16\pi\omega^2} \nabla |\mathbf{E}_0|^2, \tag{2}$$

where N_α and $\omega_{L\alpha}^2 = 4\pi N_\alpha e_\alpha^2 / m_\alpha$ are the density and the plasma frequency of the species α respectively. In a cold isotropic plasma the dielectric permittivity has the form [9, 11]

$$\varepsilon = 1 - \frac{\omega_{L\alpha}^2}{\omega^2}.$$

In this case the expression for the ponderomotive force acting on a unit volume of plasma has the form

$$\langle \mathbf{f}_\alpha \rangle = -\frac{1}{16\pi} (\varepsilon - 1) \nabla |\mathbf{E}_0|^2. \tag{3}$$

In a more general form the expression (3) can be written as

$$\langle \mathbf{f}_\alpha \rangle = \frac{\varepsilon_{ij} - \delta_{ij}}{16\pi} \nabla E_{0_i} E_{0_j}, \tag{4}$$

where ε_{ij} and δ_{ij} are the dielectric and unit tensors respectively. As can be seen from (1), (3) or (4) this force has a potential form. In general, the dielectric tensor strongly depends on geometry of the electric and magnetic fields. Several methods to obtain this tensor are shown in Refs. 9, 11, and 12.

The second nonlinear mechanism is related to the time dependence of the HF field amplitude. In particular, the force acting on the plasma particles arises when the HF field amplitude increases with time. Due to the time dependence of the amplitude in the expression for the stationary ponderomotive force (1), (3) or (4) new terms will appear. In the literature, the expression for the ponderomotive force, which includes time dependent terms, is known as the non-stationary ponderomotive force.

It is a fact that the magnitude of the ponderomotive force is small but with the advent of new radiation sources like lasers and masers capable of delivering peak powers [13, 14], exceeding the tera-watt level the concept of the ponderomotive force has acquired a renewed interest. Recently, the problem for obtaining an expression for the non stationary ponderomotive force of a HF field has been discussed extensively [15]. Among the most important applications are the following: the beat-wave and weak field particle acceleration methods [16–18], the ion cyclotron isotope separation [19–22], the generation of intense magnetic fields using the inverse Faraday effect [23–25], the generation of driven currents by non inductive methods [26–28] and recently a method has been proposed using the ponderomotive force, to produce a plasma edge rotation in tokamaks in order to suppress, by a forming thermal barrier, the turbulence resulting from the anomalous transport and increasing the energy confinement time in these machines [29–31].

An expression for the ponderomotive force can be realized using single particle [32–34], hydrodynamic [15, 35, 36] or kinetic approaches [15, 37]. As can be found in the literature, the expressions for the non-stationary ponderomotive force obtained in these approaches differ. This constitutes the origin of controversy between the expressions for the energy-momentum tensors proposed by Minkowski and Abraham [38, 39].

This paper is organized as follows: in Sect. 1 the basic equations are obtained. In Sect. 2 an expression for the non stationary ponderomotive force is obtained where the collisionless limit is analyzed.

2. Basic equations

The interaction of a HF field with plasma particles will be described using both the hydrodynamic plasma model proposed in Ref. 40, considering a collisional term and Maxwell equations:

$$\frac{\partial \mathbf{v}_\alpha}{\partial t} + (\mathbf{v}_\alpha \cdot \nabla)\, \mathbf{v}_\alpha = \frac{e_\alpha}{m_\alpha}\left[\mathbf{E} + \frac{1}{c}\mathbf{v}_\alpha \times \mathbf{B}\right] - \nu_\alpha \mathbf{v}_\alpha, \tag{5}$$

$$\frac{\partial n_\alpha}{\partial t} + \nabla \cdot (n_\alpha \mathbf{v}_\alpha) = 0, \tag{6}$$

$$\nabla \times \mathbf{B} = \frac{1}{c}\frac{\partial \mathbf{E}}{\partial t} + \frac{4\pi e_\alpha}{c} n_\alpha \mathbf{v}_\alpha, \tag{7}$$

$$\nabla \times \mathbf{E} = -\frac{1}{c}\frac{\partial \mathbf{B}}{\partial t}, \tag{8}$$

$$\nabla \cdot \mathbf{E} = 4\pi e_\alpha n_\alpha, \tag{9}$$

where ν_α is the effective collision frequency between particles. Assuming that electric $\mathbf{E}$ and magnetic $\mathbf{B}$ fields, the velocities $\mathbf{v}_\alpha$ and the densities n_α have all a slow and rapid time dependences, they can be written in the form

$$\mathbf{E} = \langle \mathbf{E} \rangle + \widetilde{\mathbf{E}}, \qquad \mathbf{B} = \langle \mathbf{B} \rangle + \widetilde{\mathbf{B}},$$
$$\mathbf{v}_\alpha = \langle \mathbf{v}_\alpha \rangle + \widetilde{\mathbf{v}}_\alpha, \qquad n_\alpha = \langle n_\alpha \rangle + \widetilde{n}_\alpha, \tag{10}$$

where the angle brackets denote an averaging over time [40]

$$\langle x(t)\rangle = \frac{1}{t_0}\int_t^{t+t_0} \widetilde{x}(t')\,dt'.$$

The time interval t_0 is large compared with the characteristic time τ of variation of the fast variables and is small compared with the characteristic time of variation of the slow variables.

It will be considered that the slow and fast variables vary sufficiently smoothly in space, *i.e.*,

$$\frac{L}{\tau}, \frac{\lambda}{\tau} \gg |\langle \mathbf{v}_\alpha\rangle|, |\langle \widetilde{\mathbf{v}}_\alpha\rangle|,$$

where L and λ denote the characteristic distances over which these quantities vary, respectively. In this case, it can be shown [40] with respect to the HF field amplitude $\mathbf{E}_0$, that in the equations for the slow variables it is sufficient to consider the linear approximation and in the equations for the fast variables it is necessary to use the quadratic approximation.

Substituting (10) into Eqs. (5)-(9) and averaging in time, the following equations for the slow quantities are obtained:

$$\frac{\partial}{\partial t}\langle \mathbf{v}_\alpha\rangle + (\langle \mathbf{v}_\alpha\rangle\cdot\nabla)\langle \mathbf{v}_\alpha\rangle = \frac{e_\alpha}{m_\alpha}\langle \mathbf{E}\rangle - \langle(\widetilde{\mathbf{v}}_\alpha\cdot\nabla)\widetilde{\mathbf{v}}_\alpha\rangle + \frac{e_\alpha}{m_\alpha}\left\langle \widetilde{\mathbf{v}}_\alpha\times\widetilde{\mathbf{B}}\right\rangle - \nu_\alpha\langle \mathbf{v}_\alpha\rangle, \quad (11)$$

$$\frac{\partial}{\partial t}\langle n_\alpha\rangle + \nabla\cdot(\langle n_\alpha\rangle\langle \mathbf{v}_\alpha\rangle + \langle \widetilde{n}_\alpha\widetilde{\mathbf{v}}_\alpha\rangle) = 0, \quad (12)$$

$$\nabla\times\langle \mathbf{E}\rangle = -\frac{1}{c}\frac{\partial}{\partial t}\langle \mathbf{B}\rangle, \quad (13)$$

$$\nabla\times\langle \mathbf{B}\rangle = \frac{4\pi}{c}\sum_\alpha e_\alpha(\langle n_\alpha\rangle\langle \mathbf{v}_\alpha\rangle + \langle \widetilde{n}_\alpha\widetilde{\mathbf{v}}_\alpha\rangle) + \frac{1}{c}\frac{\partial}{\partial t}\langle \mathbf{E}\rangle, \quad (14)$$

$$\nabla\cdot\langle \mathbf{E}\rangle = 0. \quad (15)$$

Equations (11)–(15) were obtained using the cuasi-neutrality condition. Also, it can be noticed that the influence of the rapidly varying motion on the slow motion is taken into account in terms of the high frequency pressure and the nonlinear force in (11) (second and third terms on the right hand side) and in terms of the drag flow $\langle \widetilde{n}_\alpha\widetilde{\mathbf{v}}_\alpha\rangle$ in (12) and (14).

3. Non stationary ponderomotive force

It will be assumed that the HF field is described as

$$\widetilde{\mathbf{E}}(\mathbf{r},t) = \frac{1}{2}[\mathbf{E}_0(\mathbf{r},t)\exp(-i\omega t) + \text{c.c.}], \quad (16)$$

where $\mathbf{E}_0(\mathbf{r},t)$ is the slowly varying HF field amplitude. Considering the terms to first order in temporal derivatives, the following equations for the fast variables are obtained from (5), (6) and (8)

$$\frac{\partial\widetilde{\mathbf{v}}_\alpha}{\partial t} = \frac{e_\alpha}{m_\alpha}\widetilde{\mathbf{E}} - \nu_\alpha\widetilde{\mathbf{v}}_\alpha,$$

$$\frac{\partial\widetilde{n}_\alpha}{\partial t} + \langle n_\alpha\rangle\nabla\cdot\widetilde{\mathbf{v}}_\alpha = 0,$$

$$\nabla\times\widetilde{\mathbf{E}} = -\frac{1}{c}\frac{\partial\widetilde{\mathbf{B}}}{\partial t}.$$

Solutions of these equations within the approximation mentioned above are the following:

$$\widetilde{\mathbf{v}}_\alpha = \frac{e_\alpha}{2m_\alpha(\nu_\alpha - i\omega)}\left\{\mathbf{E}_0 - \frac{1}{\nu_\alpha - i\omega}\frac{\partial\mathbf{E}_0}{\partial t}\right\} \times\exp(-i\omega t) + c.c., \quad (17)$$

$$\widetilde{n}_\alpha = -\frac{\langle n_\alpha\rangle e_\alpha}{2m_\alpha(\nu_\alpha - i\omega)} \times\frac{i}{\omega}\nabla\cdot\left[\mathbf{E}_0 - \left(\frac{i}{\omega} + \frac{1}{\nu_\alpha - i\omega}\right)\frac{\partial\mathbf{E}_0}{\partial t}\right] \times\exp(-i\omega t) + c.c. \quad (18)$$

$$\widetilde{\mathbf{B}} = -\frac{ic}{2\omega}\nabla\times\left(\mathbf{E}_0 - \frac{i}{\omega}\frac{\partial\mathbf{E}_0}{\partial t}\right)\exp(-i\omega t) + c.c. \quad (19)$$

Using (17) and (18) as well as the notation introduced in Ref. 35, the drag flow $\langle \widetilde{n}_\alpha\widetilde{\mathbf{v}}_\alpha\rangle$ takes the form

$$\langle \widetilde{n}_\alpha\widetilde{\mathbf{v}}_\alpha\rangle = \frac{1}{e_\alpha}\mathbf{j} + \Gamma_\alpha, \quad (20)$$

where

$$\mathbf{j} = \frac{i\langle n\rangle e_\alpha^2}{4m_\alpha^2\omega(\nu_\alpha^2 + \omega^2)}\nabla\times(\mathbf{E}_0\times\mathbf{E}_0^*), \quad (21)$$

is the magnetization current and

$$\Gamma_\alpha = \frac{\langle n\rangle e_\alpha^2}{4m_\alpha^2\omega(\nu_\alpha^2+\omega^2)} \times\left\{i(\mathbf{E}_0\cdot\nabla)\mathbf{E}_0^* - \frac{1}{\omega}\mathbf{E}_0\left(\nabla\cdot\frac{\partial\mathbf{E}_0^*}{\partial t}\right) - \frac{i\nu_\alpha}{\nu_\alpha^2+\omega^2}\left[\mathbf{E}_0\left(\nabla\cdot\frac{\partial\mathbf{E}_0^*}{\partial t}\right) + \frac{\partial\mathbf{E}_0}{\partial t}(\nabla\cdot\mathbf{E}_0^*)\right] - \frac{\omega}{\nu_\alpha^2+\omega^2}\left[\mathbf{E}_0\left(\nabla\cdot\frac{\partial\mathbf{E}_0^*}{\partial t}\right) - \frac{\partial\mathbf{E}_0}{\partial t}(\nabla\cdot\mathbf{E}_0^*)\right] + c.c.\right\}. \quad (22)$$

Introducing the relative velocity [35] which describes the conductivity current

$$\mathbf{u}_\alpha = \langle \mathbf{v}_\alpha\rangle + \frac{1}{\langle n_\alpha\rangle}\Gamma_\alpha, \quad (23)$$

and assuming that $\langle \mathbf{E} \rangle = 0$, the equation (11) takes the form

$$m_\alpha \langle n_\alpha \rangle \left[\frac{\partial \mathbf{u}_\alpha}{\partial t} + \nu_\alpha \mathbf{u}_\alpha + (\mathbf{u}_\alpha \cdot \nabla)\, \mathbf{u}_\alpha \right] = -m_\alpha \langle n_\alpha \rangle \langle (\widetilde{\mathbf{v}}_\alpha \cdot \nabla)\, \widetilde{\mathbf{v}}_\alpha \rangle + \frac{e_\alpha}{c} \langle n_\alpha \rangle \left\langle \widetilde{\mathbf{v}}_\alpha \times \widetilde{\mathbf{B}} \right\rangle + m_\alpha \frac{\partial \Gamma_\alpha}{\partial t} + \nu_\alpha m_\alpha \Gamma_\alpha \equiv \mathbf{f}_\alpha. \quad (24)$$

This expression constitutes the general form of the ponderomotive force. Substituting (17)-(19) in (24), it takes the form

$$\begin{aligned} \mathbf{f}_\alpha = &-\frac{\langle n_\alpha \rangle e_\alpha^2}{4m_\alpha (\nu_\alpha^2 + \omega^2)} \nabla |\mathbf{E}_0|^2 \\ &+ \frac{\langle n_\alpha \rangle e_\alpha^2}{4m_\alpha (\nu_\alpha^2 + \omega^2)} \left\{ \frac{i\nu_\alpha}{\omega} [\mathbf{E}_0 \times (\nabla \times \mathbf{E}_0^*) + \mathbf{E}_0 \cdot \nabla \mathbf{E}_0^*] - \frac{\nu_\alpha - i\omega}{\nu_\alpha^2 + \omega^2} \mathbf{E}_0 \cdot \nabla \frac{\partial \mathbf{E}_0^*}{\partial t} - \frac{\nu_\alpha + i\omega}{\nu_\alpha^2 + \omega^2} \frac{\partial \mathbf{E}_0}{\partial t} \cdot \nabla \mathbf{E}_0^* \right. \\ &- \frac{\nu_\alpha + i\omega}{\omega^2} \mathbf{E}_0 \times \left(\nabla \times \frac{\partial \mathbf{E}_0^*}{\partial t} \right) - \frac{i (\nu_\alpha + i\omega)^2}{\omega (\nu_\alpha^2 + \omega^2)} \frac{\partial \mathbf{E}_0}{\partial t} \times (\nabla \times \mathbf{E}_0^*) + \frac{i}{\omega} \frac{\partial}{\partial t} (\mathbf{E}_0 \cdot \nabla \mathbf{E}_0^*) \\ &\left. + \frac{\nu_\alpha}{\omega} \left[-\frac{1}{\omega} \mathbf{E}_0 \nabla \cdot \frac{\partial \mathbf{E}_0^*}{\partial t} - \frac{i\nu_\alpha}{\nu_\alpha^2 + \omega^2} \frac{\partial}{\partial t} (\mathbf{E}_0 \nabla \cdot \mathbf{E}_0^*) - \frac{\omega}{\nu_\alpha^2 + \omega^2} \left(\mathbf{E}_0 \nabla \cdot \frac{\partial \mathbf{E}_0^*}{\partial t} - \frac{\partial \mathbf{E}_0}{\partial t} \nabla \cdot \mathbf{E}_0^* \right) \right] + c.c. \right\}. \quad (25) \end{aligned}$$

In the collisionless limit ($\nu_\alpha = 0$), the expression (25) is reduced to that obtained in Refs. 35, 36 (in the case of an isotropic plasma). The first term in (25) is the known stationary ponderomotive force (3).

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