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Ponderomotive forces and potentials in two species relativistic plasmas

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ABSTRACT

The ponderomotive force associated with a light wave of variable amplitude drives many phenomena that occur in inertial confinement fusion and particle acceleration experiments. The existing formula for the ponderomotive force was derived under the assumption that the quiver speed of electrons oscillating in the applied electric field is much less than the speed of light. With the advent of intense laser pulses, it is important to extend this formula to electron quiver speeds that are comparable to the speed of light. We investigate the interactions of light fields with particles in two species plasmas. The equation of motion of a charged particle in an electromagnetic field and the motion of a single particle in a plane wave is investigated. Furthermore, non relativistic and relativistic ponderomotive force and potential is obtained.

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INTRODUCTION

The concept of ponderomotive force is well known for its widespread applications in plasma physics, in laser physics and in many other branches in physics. In continuum physics (classical field theory) ponderomotive forces are interpreted as time- averaged forces acting on an element of a medium because either the field or the medium *per se* is inhomogeneous (Bituk and Federov, 1999; Landau and Lifshitz, 1984; Lundin and Guglielmi, 2006; Bartell, 1967).

Time-averaged over a field cycle forces acting on charged particles in a spatially inhomogeneous electromagnetic field are usually called Ponderomotive Forces(Tajima and Dawson, 1979). In the nonrelativistic regime these forces always push the particles away from high-field areas and into the low-field areas (Clayton *et al*., 1993). In many cases these forces have a non-relativistic nature. However, in application to electrons, with advent of laser technology, Ponderomotive forces can enter a strongly relativistic domain, (Startsev and Mckinstrie, 1997) where the laser field may readily exceed a relativistic scale $g = eE/m$. Considering quasi-optical and geometrical optics approximations to handle the Ponderomotive force also relies on adiabatic approximation, whereby one can separate “slow” and “fast” motion to obtain a time-independent “ponderomotive” potential for the “slow” motion proportional to a new relativistic ponderomotive gradient force.

Particle accelerators are necessary to the scientists in order to study the physics of high energies and also have many applications in various domains such as medical imaging, radiotherapy and electronic circuits etching. The principle is to accelerate charged particles by using a strong electric field. However, the conventional accelerators cannot sustain fields above 10 to 50 MV/m because of material breakdown at the walls of the device. This led the scientists to build kilometer-long accelerators in order to reach higher and higher energies. The alternative consisting in the use of electric fields in a plasma began to be theorized in the 80s. The main advantage is that a plasma can sustain very strong electric fields, higher than 100 GV/m. The accelerating electric field can be created by the interaction between the plasma and a laser beam or an electron beam (Esarey *et al*., 1995; Faure *et al*., 2004; Leemans *et al*., 2006).

Ponderomotive Force:

Interaction of Light Fields with Particles:

In terms of the vector potential, the equation of motion of a charged particle in an electro-magnetic field has the form (Bituk and Federov, 2000; Bonse and Hart, 1965)

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$$\frac{\partial \mathbf{p}}{\partial t} + (\mathbf{v} \cdot \nabla)\mathbf{p} = e\left(\frac{\partial \mathbf{A}}{\partial t} - \mathbf{v} \times \nabla \times \mathbf{A}\right) \tag{1}$$

Which is derived from the Lorentz force

$$\frac{d\mathbf{p}}{\partial t} = e(\mathbf{E} + \mathbf{v} \times \mathbf{B}) \tag{2}$$

in which, $\mathbf{p}$ is the kinetic momentum, $\mathbf{v}$ the fluid velocity, e the electron charge, $\mathbf{A}$ the vector potential and $\mathbf{E}$, $\mathbf{B}$ are the electric and magnetic fields of the wave , respectively. It is also necessary to mention that in obtaining equation (1) the Coulomb gauge

$$\nabla \cdot \mathbf{A} = 0 \tag{3}$$

And the identity

$$\frac{\mathrm{d}}{\mathrm{dt}} = \frac{\partial}{\partial t} + v \cdot \nabla \tag{4}$$

are used.

A Single Electron in a Plane Wave:

Although this is the most basic light-particle interaction, all other effects such as the ponderomotive force, self-focusing or driving a plasma wave are in the end based on the behavior of each single electron in a light wave with relativistic intensities. For a comprehensive understanding of these collective processes, the basic characteristics of this simple single-electron motion will be discussed.

According to the Noether theorem, the two symmetries of a plane wave correspond to two conservation laws for the electron motion:

The transverse momentum $p_\perp$ is always conserved. It follows,

$$\gamma_\perp = (1 + a^2)^{\frac{1}{2}} \tag{5}$$

For the longitudinal momentum p_x it holds

$$E - cp_x = mc^2 \tag{6}$$

Then, The energy of a relativistic electron in the coordinate system of the laser pulse can be written as:

$$E = \gamma\, mc^2 = \sqrt{(mc^2)^2 + p_x^2 c^2 + p_\perp^2 c^2} \tag{7}$$

The relativistic is defined as

$$\gamma = \frac{1}{\sqrt{1-\beta^2}} = \left[1 + \left(\frac{p}{m_e c}\right)^2\right]^{\frac{1}{2}} \tag{8}$$

in which $\beta = v/c$.

Non relativistic ponderomotive Force:

The interaction of a single electron with an electromagnetic wave becomes more interesting, if, instead of a plane wave, one considers a spatially and temporally limited pulse e.g. with a Gaussian envelope. As will be seen, although in principle following the electric field (quiver motion), electrons drift away from regions of higher intensity.

In the limit $v << 1$ the equation of motion for an electron in a light wave polarized along the x direction and propagation along z reduces to

$$\frac{\partial v_x}{\partial t} = -\frac{e}{m} E_x(x) \tag{9}$$

The Taylor expansion of an electric field gives

$$E_x(x,t) = E_{x,A}(x,t)\cos(\varphi) + x\frac{\partial E_{x,A}(x,t)}{\partial x}\cos(\varphi) + \ldots \tag{10}$$

in which

$$\varphi = \omega_0 t - k_z z \tag{11}$$

To the lowest order the electron directly follows the field and moves with the quiver velocity. However, from the cycle-averaged equation of motion for the second order field

$$\left\langle \frac{\partial v_x}{\partial t} \right\rangle_T = \left\langle \frac{e^2}{m^2\omega^2 c^2} E_{x,A} \frac{\partial E_{x,A}(x,t)}{\partial t} \cos(\varphi)^2 \right\rangle_T = \frac{e^2}{4m^2\omega^2} \frac{\partial E_{x,A}^2}{\partial x} \quad (12)$$

the non-relativistic ponderomotive force

$$F_p = m\left\langle \frac{\partial v_x}{\partial t} \right\rangle \quad (13)$$

can be determined as

$$\mathbf{F}_p = -\frac{e^2}{4m\omega_0^2} \nabla E_A^2 \quad (14)$$

Furthermore the ponderomotive force is a conservative force that can be derived from a potential U_p via $\mathbf{F}_p = -\nabla U_p$ with

$$U_p = \frac{e^2}{4m\omega_0^2} E_A^2 \quad (15)$$

Relativistic ponderomotive Force:

In the relativistic case, the equation of motion assuming that again the motion can be separated into a fast oscillating part, that directly follows the vector potential $p = eA$ and a slow component, the relativistic ponderomotive force can be determined

$$\mathbf{F}_{p,rel} = -\frac{me^2}{2\gamma} \nabla A^2 = -mc^2 \nabla \gamma \quad (16)$$

Summaries:

We investigated the interaction of light fields with particles. We obtained the energy of a relativistic electron in the coordinate system of the laser pulse and the relativistic factor. Also, we find the non relativistic and relativistic ponderomotive force.

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