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Transport Properties of Suprathermal Electron Generation in Plasma Channel by Intense Short-Pulse Laser

Sonu Sen
Department of Physics,
Shri Neelkantheshwar Government Post Graduate College, Khandwa, 450001, India

Abstract: An intense short-pulse laser through underdense plasma expels electrons and ions from the focal spot by the ponderomotive pressure and forms a channel, which acts as a propagation guide for the laser beam. Transport properties of suprathermal electrons has been observed peaked in the direction of laser propagation and having energy spectra of thermal character. Often one finds two populations of the electron with two distinct temperatures. Based on this analogy in the present paper we make an analytical investigation of transport properties that produce such electron distributions introduced through relativistic ponderomotive force. For the given values of plasma frequency and laser frequency, two populations of the electron with two distinct temperatures are characterized by dimensionless power and dimensionless beam width parameter. The dependence of the dielectric constant of plasma on dimensionless power in relativistic laser-plasma interaction has been studied. The variation of beam width with the distance of propagation has also been obtained for typical values of parameters in plasma for both populations of the electron with distinct temperatures.

***Key Words* – Self-focusing, Suprathermal Electron, Plasma Channel.**

I. Introduction

The basic transport properties involved in laser-plasma interaction, up to 10^{17} W/cm^2, are now well understood; on the other hand, a large number of fundamental issues remain open in the study of the ultrahigh intensity relativistic interaction regime. At ultrahigh intensities, transport properties of the laser-electron interaction become highly nonlinear, thus, resulting in a wide variety of new and interesting phenomena. Now it has become possible to produce suprathermal electrons in plasma as seen in recent experiments with solid targets [1], preformed plasmas [2], or pulsed gas jets [3]. The fast ignitor concept [4], relevant to the inertial confinement fusion (ICF), enhances the interest in this process as well as in laser propagation and channel formation. The channel formation process can be enhanced by the cumulative effects of ponderomotive and relativistic self-focusing which increase the laser intensity. In the present paper, we have made an analytical investigation followed by numerical calculations to study transport properties of suprathermal electron generation in the plasma channel by an intense short-pulse laser. In section II mathematical formulation is presented for the transport properties with two-electron temperatures. Result and discussion are made in section III with experimental relevance.

II. Mathematical formalism

For a circularly polarized light, the ponderomotive force that separately accelerated the two-electron fluid components is given by [5].

$$F_{h,c} = -(\omega_{ph,c}^2 / 2\omega^2)\nabla I \sim n_{h,c}\nabla I \qquad (1)$$

the suffix h and c denote hot and cold electron, m_0 is the rest mass of the electron, and $n_{h,c}$ is the density of hot and cold electrons. The relativistic Lorentz factor γ depends on the electric field strength **E**. The factor γ for a circularly polarized wave of frequency 'ω' is given as

$$\gamma = \left[1 + (e/m_0\omega c)^2 E^2\right]^{1/2} \qquad (2)$$

An important consequence of this is the increase of the energy density of the laser field up to extremely high values in the region around the focal point that means nonlinear forces are developing which drive electrons and ions out of the focus region. Following [6], the self-focusing equation can be written as

$$\varepsilon_0(z)\frac{d^2 f}{dz^2} = \left(\frac{c^2}{r_0^4\omega^2} + \frac{\varepsilon_1(r,z)}{r^2} f^4\right) \qquad (3)$$

The parameter 'f' is the beam width parameter, which can be defined as

$$r(z) = r_0 f(z) \qquad (4)$$

r_0 being the beam width at z = 0. Using dimensionless variables, $\xi = (ze/r_0^2\omega)$ and $\rho = (r_0\omega/c)$ equation (3) reduces to

$$\varepsilon_0(f)\frac{d^2 f}{d\xi^2} = \left\{1 + \rho^2 \frac{r_0^2}{r^2}\varepsilon_1(r,f) f^2\right\}\frac{1}{f^3} \qquad (5)$$

The z variable in $\varepsilon_0(z)$ and $\varepsilon_1(r, z)$ has been replaced by 'f', which is a function of z alone. Knowing $\varepsilon_0(f)$ and $\varepsilon_1(r, f)$ one can integrate equation (5) numerically to obtain as a function of ξ. The effective dielectric constant due to ponderomotive force with relativistic nonlinearity comes out as

$$\varepsilon = 1 - \Omega_{ph,c}^2\left(1+\alpha^2 EE^*\right)^{-1/2} - \frac{\Omega_{ph,c}^2}{2}\left(1+\alpha^2 EE^*\right)^{-3/2} \qquad (6)$$

here $\alpha = (e/m_0\omega c)$ and $\Omega_{ph,c} = (\omega_{ph,c}/\omega)$

$$EE^* = \sqrt{\frac{\varepsilon_0(1)}{\varepsilon_0(f)}}\left(\frac{E_{00}^2}{f^2}\right)\exp\left(-\frac{r^2}{r_0^2 f^2}\right) \qquad (7)$$

Using equation (7) in equation (6) and substituting $p = \alpha^2 EE^*$ and replacing $\exp(-r^2/r_0^2 f^2)$ by $(1 - r^2/r_0^2 f^2)$ in paraxial approximation one obtains

$$\varepsilon_0(f)\frac{d^2 f}{d\xi^2} = \left\{1 - \rho^2 \frac{\Omega_{ph,c}^2 p}{2}(1+p)^{-3/2}\right\}\frac{1}{f^3} \qquad (8)$$

For $(d^2 f/d\xi^2)$ to vanish equation (8) requires at $z = 0$ ($f = 1$),

$$\rho_0^2 = \frac{2}{\Omega_{ph,c}^2}\frac{(1+p_0)^{3/2}}{p_0} \qquad (9)$$

Equation (9) expresses the dimensionless beam width ρ_0 (at $f = 1$) as a function of a dimensionless quantity p_0 proportional to E_{00}^2 and hence, also to the initial beam power.

III. Results and Discussion

For the analysis of transport properties, we arrive at a defined set of equations for nonlinear dielectric function in a two-electron temperature plasma given by equation (6), relativistic self-focusing equation (8), and the critical power by equation (9). The function of equation (9) can be drawn, as a curve in the (p_0, ρ_0) plane and is generally regarded as the critical power curve as shown in Fig. 1. Here we draw two critical curves corresponding to cold electron $(\omega_p/\omega)^2 = 0.6$ and hot electron $(\omega_p/\omega)^2 = 1.1$. If the initial value of p and ρ of a laser beam is such that the point (p_0, ρ_0) lies on the critical curve the value of $(d^2f/d\xi^2)$ will vanish at $\xi = 0$ ($z = 0$) since the initial value of $(df/d\xi)$ is zero, the value of $(df/d\xi)$ continues to be zero as the beam propagates through the plasma. Hence, the initial value of 'f', which is unity (at $z = 0$), will remain unchanged. Thus, the beam propagates without any change in its beam width. Such propagation is known as uniform waveguide propagation. For initial point (p_0, ρ_0) of the beam lying below the critical curve that is on the same side of the curve as the origin $(d^2f/d\xi^2) > 0$ and for the points lying on the other side $(d^2f/d\xi^2) < 0$, therefore, for the initial point not lying on the critical curve the beam width parameter will either increase (for the point below) or decrease (for the point above), as the beam propagates.

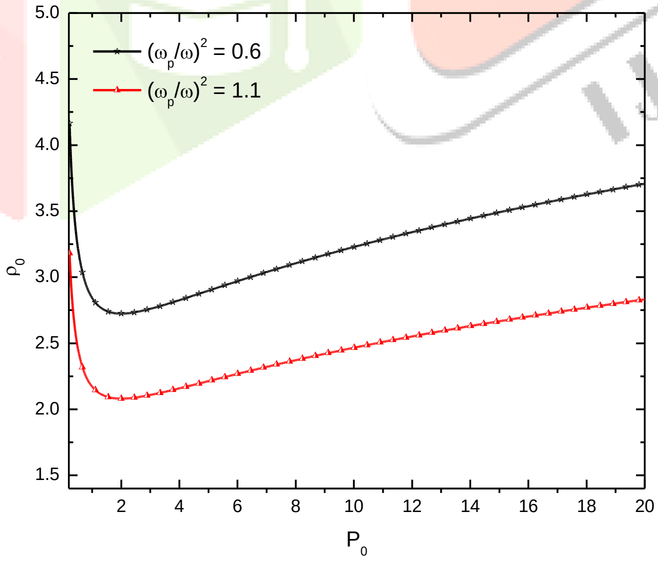

FIGURE 1. The critical curves between dimensionless initial beam width versus dimensionless initial beam

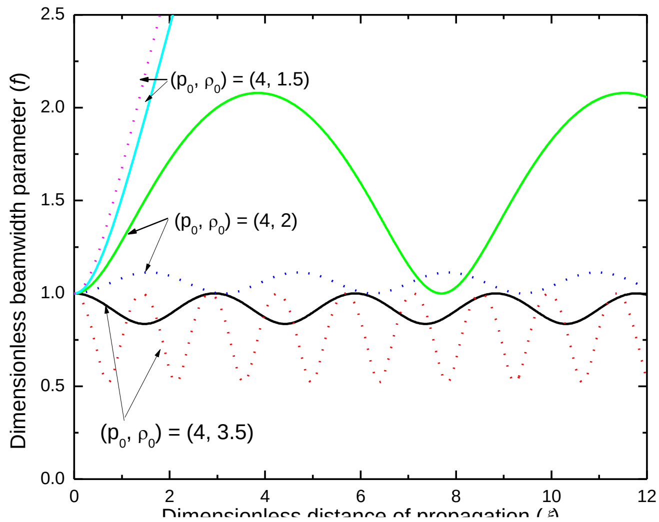

FIGURE 2. Beam width parameter f versus dimensionless distance of propagation ξ for $(\omega_p / \omega)^2 = 0.6$ (solid line) and $(\omega_p / \omega)^2 = 1.1$ (dotted line).

The f versus ξ graphs have been obtained by numerically integrating equation (8) and are illustrated in Fig. 2. The (p_0, ρ_0) coordinates for these three sets of curves for hot electron and cold electron are (4, 3.5), (4, 2), and (4, 1.5). From the figure, it is evident that hot electrons converge/diverge faster as compared to cold electrons. The above situation is attributed to the fact that thermal de Broglie's wavelength of the hot electron is less as compared to cold electrons. As a result, self-focusing takes at an earlier time for hot electrons or self-focusing increases, hence the channel formation process can be enhanced by relativistic self-focusing which increases the laser intensity and generates suprathermal electrons

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