Guiding of intense laser beam under the combined effect of Ponderomotive and Relativistic nonlinearity

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Abstract

The guiding of intense laser pulses in a plasma channel formed by short ionizing laser pulses has been studied under the combined effect of ponderomotive and relativistic nonlinearity by using Variational technique. Due to self-defocusing of an ionizing short laser prepulse, the plasma channel formed is axially nonuniform. When a second laser beam is passed through a performed plasma channel, convergence and divergence of the beam is observed due to the relative competition of the refractive and diffractive terms. Propagation of guided laser beam over 5.1 Rayleigh lengths has been observed. The results of the analysis are useful in understanding physics issues of ICF involved in laser-plasma interactions.

Key words : Guiding, relativistic, ponderomotive, nonlinear-medium

1 Introduction

The development of ultra high intensity lasers over the past several years has led to a number of applications such as X-ray lasers (Burnett and Enright, 1990), plasma based accelerators (Kitagaw *et al.*, 1992), laser plasma channeling (Young *et al.*, 1995) and fast ignitions schemes in laser fusion (Tabak *et al.*, 1994) etc. Inertial confinement fusion (ICF) require a long propagation distance in the plasma with high laser intensity. For this laser pulse must be guided for distances significantly greater than vacuum diffraction length (Rayleigh length). The ultraintense laser pulse can generate different types of nonlinearities at different timescales $\tau_{pe} < \tau < \tau_{pi}$, where τ is the laser-pulse duration, τ_{pi} is the ion plasma period, and τ_{pe} is the electron plasma period when relativistic and ponderomotive nonlinearities are operative. Since both the nonlinearities alter the propagation of a laser beam through plasma so it is important to study their combined effect.

The physics of guiding laser pulse is as follow, we create the channel by focusing intense prepulse. Since the prepulse has gaussian radial profile so the the plasma density that results has peak on the axis and falls rapidly with radial distance away from the axis before the diffusion of plasma sets in. So the refractive index is minimum on the axis and increases toward the edge and therefore the medium behaves as defocusing medium. Due to defocussing of the laser beam, axially noinuniform plasma channel is formed.

Once the prepulse is gone, plasma created by prepulse diffuses radially away from the axis and therefore the refractive index becomes maximum on the axis and decreases toward the edge and medium behaves like focusing medium. We have used Variational technique (Anderson, 1983) to study the guiding of intense delayed laser beam in an axially nonuniform plasma channel created by the prepulse under the combined effect of ponderomotive and relativistic nonlinearity.

In section 2 and 3, we have developed a Variational approach of self-defocussing of prepulse and guided pulse respectively. Discussion of the result is presented in section 4.

2 Self-defocusing of ionising laser pulse

Consider the propagation of a Gaussian laser beam of frequency ω_0 through a gas along z- axis. The laser ionizes the gas via tunnel ionization in a time shorter than the pulse duration (Leemans *et al.*, 1992). Durfee and Milchberg, (1993) in their code, have indeed obtained sharp density fallout beyond r$\sim r_o/2$. Such a sharp plasma density profile is modelled by (Liu and Tripathi, 1994) as.

$$\omega_p^2 = \omega_{po}^2 \exp\left(\frac{-E_a'}{|E|}\right), \tag{1}$$

The dielectric function of the plasma may be written as (Liu and Tripathi, 1994).

$$\epsilon = \epsilon_o + \epsilon_2 r^2, \tag{2}$$

where $\epsilon_o = \epsilon|_{r=0} = 1 - \left(\frac{\omega_{po}^2}{\omega_o^2}\right)\exp[-E_a'/|E_{oo}|]$,

$$\epsilon_2 = \frac{\partial \epsilon}{\partial |E|}\frac{\partial |E|}{\partial r^2}|_{r=o} = \frac{\omega_{po}^2}{2\omega_o^2}\frac{E_a'}{E_{oo}a^2(z)} \exp\left(\frac{-E_a'}{A}\right). \tag{3}$$

In the slowly varying approximation, we get the following nonlinear Schrodinger equation (NLSE):

$$2\iota k\frac{\partial E}{\partial z} + \nabla_\perp^2 E + \frac{\omega_o^2}{c^2}\epsilon_2 r^2 |E| = 0. \tag{4}$$

We have solved Eq. (4) using variational approach. We reformulate this equation into variational problem corresponding to Lagrangian L and using a trial function $E = A[z]\exp\left[-\frac{r^2}{2a^2(z)} + \iota q(z) r^2\right]$ we get the reduced problem with $< L >$ as

$$< L >= |A|^2\left(\frac{1}{2} + 2q^2a^4\right) + \iota k\left(A\frac{\partial A^\star}{\partial z} - A^\star\frac{\partial A}{\partial z}\right)\frac{a^2}{2} + k|A|^2\frac{\partial q}{\partial z}a^4 - \frac{\omega_o^2}{c^2}\epsilon_2|A|^2\frac{a^4}{2} \tag{5}$$

Taking variation with respect to A , $A^\star$, a, q etc and following the procedure of (Anderson *et al.*, 1983), we arrive at the following equation $\frac{d(A^2a_n^2)}{d\zeta} = 0$, $q = \frac{1}{a_n}\frac{da_n}{d\zeta}$,

$$\frac{d^2a_n}{d\zeta^2} = \frac{1}{2a_n^3}\left[1 + \left(\frac{\omega_p a_o}{c}\right)^2 a_n^2 \exp(-E_a'/|E|) - 2a_n^2\left(\frac{da_n}{d\zeta}\right)^2\right], \tag{6}$$

Where ($a_n = \frac{a}{a_o}$) is the normalized beam width of the prepulse and $\zeta = \frac{zc}{\omega_o a_o^2}$

3 Guided propagation of laser Beam

Once the prepulse is gone, plasma formed starts moving radially away from the axis. According to (Durfee and Milchberg, 1993) the density profile of the plasma on the arrival of the delayed second pulse is given by

$$\frac{\omega_p^2}{\omega^2} = \alpha_1(z) + \alpha_2(z) r^2 \tag{7}$$

we can express the nonlinear part of the dielectric constant of relativistic and ponderomotive nonlinearity given by the following equation (Siegrist *et al*, 1976).

$$\Phi(E_o.E_o^\star) = \frac{\omega_p^2}{\omega_o^2}\left[1 - \frac{exp(-\beta E_o.E_o^\star)}{(1+\alpha E_o.E_o^\star)^{1/2}}\right] \tag{8}$$

where $\alpha = \frac{e^2}{m_o^2 c^2 \omega_o^2}$ and $\beta = \frac{e^2}{8 m_o \omega_o^2 KT}$. Here ω_p is the plasma frequency, given by $\omega_p^2 = 4\pi n_e e^2/m_o$ where e_o and m_o are the charge and rest mass of the electron respectively, and n_e is the density of the plasma electrons. If we express the electric field of second pulse as $E = A[z]\exp\left[-\frac{r^2}{2b^2(z)} + \iota q(z) r^2\right]$, where 'b' is beam width parameter of the beam.The amplitude A as well as beam width 'b' are real function of z. In slowly varying envelope approximations, we have nonlinear Schrodinger wave equation as

$$2\iota k\frac{\partial E}{\partial z} + \nabla_\perp^2 E + \frac{\omega^2}{c^2}\epsilon_2(z) r^2 E = 0 \tag{9}$$

where $\epsilon_2(z) = -\alpha_1(z)\frac{\beta|A_0|^2}{b^2}\frac{\exp[-\beta|A_0|^2]}{(1+\alpha|A_0|^2)^{\frac{3}{2}}}\left[(1+\alpha|A_0|^2) + \frac{\alpha|A_0|^2}{2}\right] - \alpha_2(z)\frac{\exp[-\beta|A_0|^2]}{(1+\alpha|A_0|^2)^{\frac{1}{2}}}$

$k = \frac{\omega}{c}(1-\alpha_1(z))^{\frac{1}{2}}, k_o = k(z=0)$ and $\alpha_2 = 2/R_d^2(1+\zeta^2)^{\frac{1}{2}}$. We have solved Eq. (9) by using Variational technique as in section 2 and arrived at the following equation

$$\frac{d^2 b_n}{d\zeta^2} = \frac{1}{2b_n^3(1-\alpha_1)}\left[1 - \frac{\omega^2}{c^2}\frac{\alpha_2(\zeta)\exp[-\beta|A_0|^2] b_n^4 b_o^4}{(1+\alpha|A_0|^2)^{\frac{1}{2}}} - 2(1-\alpha_1) b_n^2\left(\frac{db_n}{d\zeta}\right)^2\right] \tag{10}$$

4 Discussion

Nonlinear Ordinary Differential Equations (6) and (10) are solved numerically for the following set of parameters $\frac{E_a'}{A_{oo}} = 0.5$, $\omega_{rp} = \frac{\omega_p a_o}{C} = 0.592$, $\alpha_1 = 0.7$, $a_o = 0.001$, $b_o = 0.001$ and for intensity $9.2 \times 10^{17} W/cm^2$. The results are displayed in the form of graphs in Fig.1 to Fig. 2. Equation (6) and (10) are nonlinear ordinary differential equations governing the behaviour of normalized beam width $'a_n'$ of the prepulse and $'b_n'$ of the guided pulse respectively. The first two terms on the right hand side of equation (6) and (10) are diffractive and refractive term respectively.

The last term of these equations is initially zero and counteracts the diffractive terms as the beam propagates in the plasma channel. It is obvious from the Fig.1 that the beam width of the prepulse increases monotonically leading to defocussing of the ionized prepulse. This is due to the fact that the first diffractive term on the right hand side of equation (6) is supplimented by the refractive induced defocussing second term. However with the propagation of the beam, there is finite contribution from the last term on the right hand side of equation (6), which prevents the beam from steep defocussing.

Fig. 2 also represents the variation of normalized beam width 'b_n' of the guided laser beam with the distance of propagation for the intensity $|E_0|^2 = 9.2 \times 10^{17} W/cm^2$. It is observed from the figure that b_n initially decreases with ζ acquiring a minimum $b_{min} \approx 0.768$ at around $\zeta \approx 0.85$. It is further observed that b_n varies in the range $0.768 < b_n < 1.414$ as ζ varies from 0 to 5.1. So in the present investigation laser guiding up to 5.1 Rayleigh length has been observed.

Results of the present investigation are useful for laser induced fusion.

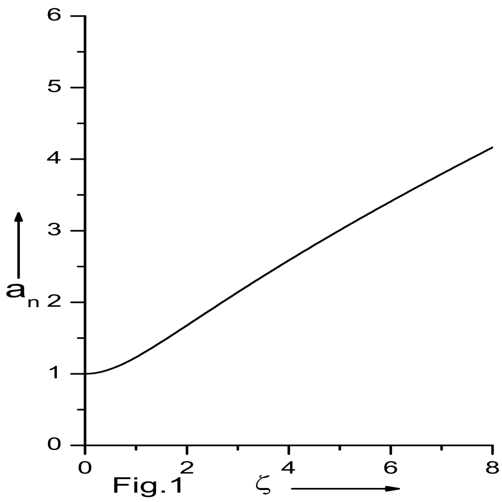

Fig.1

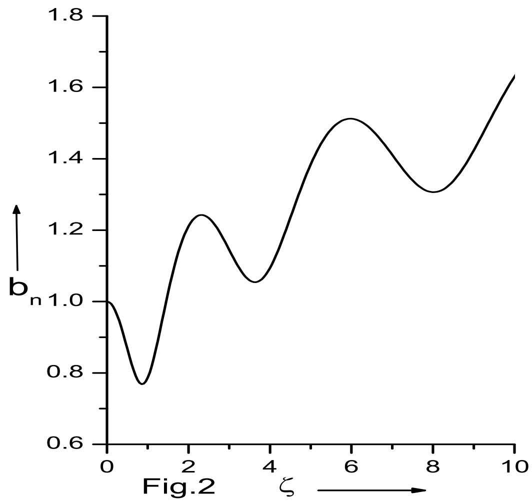

Fig.2

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