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Nonlinear propagation of Gaussian laser beam in an inhomogeneous plasma under plasma density ramp

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ABSTRACT

Nonlinear propagation of Gaussian laser beam in an inhomogeneous plasma under plasma density ramp is studied. The differential equation for beam width parameter is derived by parabolic wave equation approach under paraxial approximation. For different values of plasma density, laser intensity and initial beam width, the behavior of beam width parameter with the normalized propagation distance is examined. It is found that the beam width parameter decreases with a higher rate. The frequency of the oscillations increases while amplitude decreases and the laser beam focuses up to long distance. Further, increase in relative plasma density causes reduction in the amplitude of spot size of laser beam near the propagation axis.

1. Introduction

The theoretical and experimental study of interaction of high intensity laser beams with plasmas is a fascinating field of research which gives rise to various important applications such as plasma based accelerators [1], inertial confinement fusion [2,3], ionospheric modification [4,5] etc. For the success of these applications, the laser beam propagates over distances greater than several Rayleigh lengths [6–8]. Self-focusing is a nonlinear phenomenon which is induced due to change in the refractive of the medium. It can be relativistic [9] as well as ponderomotive [10]. The former is due to relativistic mass variation of electrons and the later is due to plasma density variations produced by ponderomotive forces. The phenomenon of self-focusing has been studied by many authors [11–16] and found that the laser and plasma parameters are important for the self-focusing of laser beam in plasma. Gupta et al. [17] found that the ion temperature causes thermal self-focusing and has a serious influence on the evolution of laser beam in plasma. However, optimum self-focusing is achieved by taking in to account the combined effect of ponderomotive and relativistic self-focusing [18].

Jafari Milani et al. [19] investigated the ponderomotive self-focusing of Gaussian laser beam and reported that the collision frequency at first causes self-focusing and then defocusing of laser beam takes place in warm collisional plasma. But, as collision frequency is increased, the self-focusing length becomes shorter with the result, larger collision frequency prevents the longer propagation of laser beam through plasma. The higher order axial electron temperature decreases the influence of collisional nonlinearity. It changes the electron density distribution and increases the dielectric constant therefore, leads to fast divergence of the laser beam [20]. However, following higher order paraxial theory with ramped density profile enhances the focusing of laser beam in plasma [21]. Again, Patil et al. [22] have found that the upward plasma density ramp tends to enhance the self-focusing significantly and the beam gets more focused while traversing several Rayleigh lengths as

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compared with uniform density relativistic plasma. Kant and Wani [23] reported that the decentered parameter and linear absorption change the nature of self-focusing/defocusing of laser beam. The absorption weakens the self-focusing effect and the density transition sets an earlier self-focusing of laser beam in plasma.

In this paper, our purpose is to analyze the impact of upward plasma density ramp on nonlinear propagation of Gaussian laser beam in an inhomogeneous plasma. The plasma density ramp profile chosen is of the form $n(\xi) = n_0 \tan(\xi/d)$. The non-linear dielectric constant of plasma is presented in ponderomotive regime. The equations governing the spot size of the laser beam are derived. The computational results in the context of plasma density, laser intensity and initial beam width are discussed and finally a brief conclusion is added. The importance of the present work lies in the fact that the upward plasma density ramp enhances the self-focusing to a greater extent in inhomogeneous plasma.

2. Nonlinear dielectric constant

The nonlinear dielectric function ε for an isotropic inhomogeneous medium can be expressed as

$$\varepsilon = \varepsilon_r(z, EE^*) - i\varepsilon_i(z, EE^*), \tag{1}$$

where, ε_r and ε_i are the functions of z and the irradiance EE^*. Further, ε_r can be expressed as:

$$\varepsilon_r(z, EE^*) = \varepsilon_0(z) + \varepsilon_s \mu(z) \frac{\varepsilon_2 EE^*}{1 + \varepsilon_2 EE^*}, \tag{2}$$

where, ε_0 and μ are functions of z. The function $\mu(z)$ is identified with the plasma frequency. In this case $\varepsilon_0(z) = 1 - \left(\omega_{p0}^2/\omega^2\right)\mu(z)$, $\varepsilon_s = \omega_{p0}^2/\omega^2$, $\varepsilon_i(z) = \mu(z)\varepsilon_i(0)$ with, $\mu(z) = \omega_p^2/\omega_{p0}^2 = \tan(\xi/d)$, $\omega_p^2 = \omega_{p0}^2 \tan(\xi/d)$ and $\omega_{p0}^2 = 4\pi n_0 e^2/m$. Where, ω_{p0} is the plasma frequency, ω is the angular frequency of incident laser beam, ε_i is the characteristic of absorption in the medium, $\mu(z)$ is characteristic of the density of dipoles, m, e and n_0 are the electron's rest mass, charge on the electron and equilibrium electron density respectively, ξ is the normalized propagation distance and d is a dimensionless parameter. In case of Gaussian beam $\varepsilon_r(z)$ can be expanded in the paraxial approximation as:

$$\varepsilon_r(z) = \varepsilon_{r0}(z) - r^2 \varepsilon_{r_2}(z). \tag{3}$$

3. Self-focusing

Consider the Gaussian laser beam propagating along the z-direction with electric vector $\vec{E}$ satisfies the scalar wave equation of the form

$$\frac{\partial^2 E}{\partial z^2} + \left\{ \frac{\partial^2}{\partial r^2} + \frac{1}{r}\frac{\partial}{\partial r} \right\} E + \frac{\omega^2}{c^2}\varepsilon(r, z)E = 0, \tag{4}$$

where, c is the speed of light in vacuum. Eq. (4) can be solved in the paraxial approximation by following the analysis of Akhmanov et al. [24] and its extension by Sodha et al. [25,26]. The solution of Eq. (4) is of the form

$$E(r, z) = A(r, z) \exp\left[-\int_0^z ik(z)dz \right], \tag{5}$$

where, $A(r, z)$ is the slowly varying envelope of the beam and k is the propagation constant of the wave which is given by $k^2 = (\omega^2/c^2)\varepsilon_{r0}(z)$. Substituting for $E(r, z)$ from Eq. (5) in Eq. (4) and neglecting $(\partial^2 A/\partial z^2)$. Under WKB approximation, one obtains

$$-2ik\frac{\partial A}{\partial z} - iA\frac{\partial k}{\partial z} - k^2 A + \frac{\partial^2 A}{\partial r^2} + \frac{1}{r}\frac{\partial A}{\partial r} + \frac{\omega^2}{c^2}\varepsilon(r, z)A = 0, \tag{6}$$

To solve Eq. (6) in the paraxial approximation, the complex amplitude $A(r, z) = A_0(r, z)\exp[-ik(z)S(r, z)]$ is considered. Here, A_0 and S are real functions of r and z and the eikonal $S(r, z) = (r^2/2)\beta(z) + \phi(z)$, where, $\beta(z) = (1/f(z))(\partial f/\partial z)$ represents the curvature of the wavefront. Real and imaginary parts of Eq. (6) are obtained as:

$$2\frac{\partial S}{\partial z} + \left(\frac{\partial S}{\partial r}\right)^2 + \left(\frac{2S}{k}\right)\frac{\partial k}{\partial z} = \frac{1}{k^2 A_0}\left(\frac{\partial^2 A_0}{\partial r^2} + \frac{1}{r}\frac{\partial A_0}{\partial r}\right) - \frac{r^2 \varepsilon_{r_2}(z)}{\varepsilon_{r_0}(z)}, \tag{7}$$

$$\frac{\partial A_0^2}{\partial z} + A_0^2\left(\frac{\partial^2 S}{\partial r^2} + \frac{1}{r}\frac{\partial S}{\partial r}\right) + \frac{\partial A_0^2}{\partial r}\frac{\partial S}{\partial r} = A_0^2\left(\frac{-\tan\left(z/dR_d\right) k\varepsilon_i(0)}{\varepsilon_{r_0}(z)} - \frac{1}{k}\frac{\partial k}{\partial z}\right). \tag{8}$$

The solution of Eq. (8) can be written as

$$A_0^2(r, z) = \left(\frac{E_0^2(z)}{f^2(z)}\right)\Im\left(\frac{r}{r_0 f(z)}\right), \tag{9}$$