Temporal evolution of Gaussaian laser pulse in a magnetized plasma

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Abstract

Temporal evolution of an intense Gaussian laser pulse propagated into the near critical density region of a magnetized plasma has been studied, taking ponderomotive nonlinearity into account. The modification of the dielectric permittivity of such plasma due to the ponderomotive force of the laser pulse has been derived. The equations governing the laser pulse dynamics in time have been achieved and numerically solved, using the eikonal function and paraxial ray approximation. The effect of magnetic field on the self-compression of the Gaussian laser pulse in the plasma has been demonstrated. It is found that , an increase in the value of external magnetic field causes an increase in the strength of the self-compression, especially in the higher values, and consequently, the self-compression occurs in shorter distance of propagation.

Keywords: Pulse compression, laser pulse propagation, magnetized plasma

Introduction

Attractive features of intense laser plasma interaction cover wide research area including laser wakefield acceleration, X-ray lasers, THz radiation generation, acceleration of charged particles, laser driven fusion and optical harmonic generation, etc [1-4]. Because of the ionized state and nonlinear nature of plasma, it can sustain extremely high laser intensities therefore the plasma medium was proposed for amplification and compression of laser pulses [5]. During high intensity laser pulse propagation through an underdense plasma numerous types of nonlinear process such as self-compression can be occurred due to the ponderomotive force effects. The ponderomotive force of high intensity laser pulse with a spatial gradient of intensity expels electrons out of the higher intensity region and modifies the electron density distribution which leads to a changed refractive index of plasma. This leads to change of the refractive index of plasma. The self-compression of laser pulse arises from the longitudinal gradient of refractive index [6].

The following work will describe the temporal characteristics of the Gaussian laser pulse in the magnetized plasma taking into account the ponderomotive nonlinearity. In this study the propagation of a laser pulse through a plasma having high density (near critical density) has been discussed. As the laser pulse propagates into the plasma, it gets self-compressed due to the combined effect of SPM and ponderomotive nonlinearity. We indicated the temporal profile of the laser pulse at different positions (or time) as it propagates in the plasma. Using the equation of motion of electrons in the steady state, the modified electron density function was obtained. Then in order to study the compression of the pulse, a nonlinear differential equation governing the dynamics of pulse was obtained and solved numerically.

THEORETICAL CONSIDERATIONS

Consider the propagation of an intense Gaussian laser pulse (in space and time) along the z axis through a plasma in which the external magnetic field is applied along z axis. The electric field of the laser pulse can be written as $E\,(r,z,t) = A\,(r,z,t)(\hat{x}+i\hat{y})\exp\left[i(\omega t-kz)\right]$, where $A(r,0,t) = A_0 exp(-r^2/2r_0^2)exp(-t^2/2\tau_0^2)$ is the complex amplitude of Gaussian pulse, r_0 is the initial beam radius and τ_0 is the initial pulse length (in time) and for a Gauusian laser pulse we can witre: $A_0^2(r,z',\tau) = \frac{A_{00}^2}{f^2 g}\exp\left(\frac{-r^2}{f^2 r_0^2}\right)\exp\left(\frac{-\tau^2}{g^2\tau_0^2}\right)$,where f represent the beam width (space) parameter and g the pulse length (time) parameter, respectively[7]. A nonlinear poneromotive force

$$\mathbf{F}_p = \frac{-m_e}{2}\mathrm{Re}\left(\mathbf{V}.\nabla\mathbf{V}^*\right) - \frac{e}{2c}\mathrm{Re}\left(\mathbf{V}^*\times\mathbf{B}\right). \qquad (1)$$

acts on electrons resulting in their density redistribution and hence changing the refractive index of plasma. Under such scheme the modified electron density is given by:

$$n_e\left(r,z,\tau\right) = n_0\exp\left(-\frac{a}{T_e}|A|^2\right) \qquad (2)$$

where $a = \frac{e^2}{4m_e\omega^2}\frac{1}{1-\Omega_c^2}\left[1+\Omega_c+\frac{\left(1+\Omega_c\right)^2}{1-\Omega_c^2}\right]$,T_e is the temperature of electron, $\Omega_c = \frac{\omega_c}{\omega}$. Substituting electric field in the wave equation and using the paraxial approximation, we obtained the equation governing the dynamics of the pulse length parameter g as

$$\varepsilon_0 \frac{\partial^2 g}{\partial \xi^2} = \frac{\beta^2}{\tau_p^4 g^3} - \frac{\beta \varepsilon_\tau}{\tau_p^2} g. \tag{3}$$

Where $\xi = z\omega/c, \rho = r_0\omega/c, \tau_p = \tau_0\omega/c$.

Results and discussion

In order to investigate the effect of the magnetic field on the one-dimensional pulse compression, Eq. (3) is solved by setting the $g = 1, g' = 0$ at $\xi = 0$. Initial laser and plasma paramerets are used as follows: $\lambda = 1064nm$, $n_e = 10^{20}\ cm^{-3}$ $T_e = 1.5keV$.

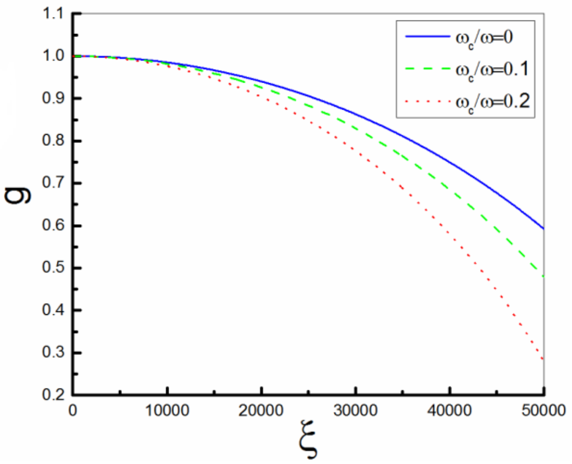

Fig 1: The variation of the dimensionless longitudinal pulse length parameter g, with normalized distance of propagation for different values of Ω_c .

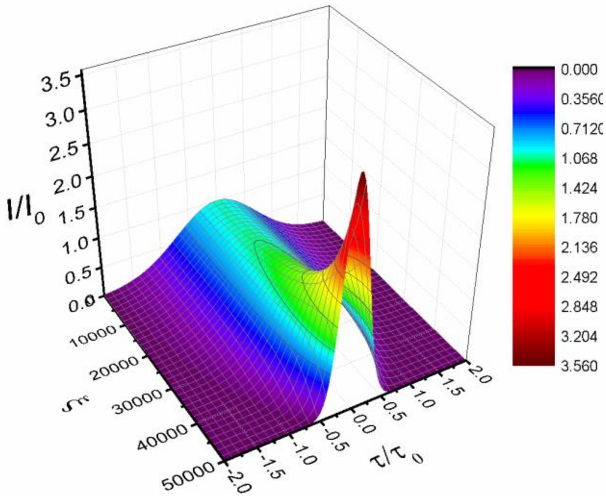

Fig 2: The variation of the normalized laser intensity for $\Omega_c = 0.2$. Other parameters are the same as those in Fig. 1.

Figure 1 depicts plots of pulse length (g) parametere versus normalized distance of propagation ξ at different values of Ω_c for initial laser intensity $I_0 = 3\times10^{15} W/cm^2$. Figure 1 shows as the laser pulse propagates through the plasma, it gets compressed and the amplitude of the pulse length parameter (g) is decreased by increasing the values of Ω_c In other words, the strength of the self-compression is enhanced by increasing the magnetic field and pulse compression occurs at a shorter distance. Surface plot of the normalized intensity I/I_0 and temporal pattern of compressed laser pulse as a function of two dimensionless parameters ξ and τ/τ_0, is shown in Fig. 2. We can see that the laser pulse is compressed and its intensity is enhanced as it propagates in the plasma due to the ponderomotive nonlinearity. The physical interpretation of this behavior can be explained as follows. The right handed polarization wave exerts a force on the electrons, causing them to move in direction of their cyclotron motion. In this case, by increasing the value of magnetic field, transverse velocity of electrons increases and leads to an increase in the nonlinear current density or nonlinearity of plasma.

Conclusions

In this analysis, the evaluation of temporal characteristics of Gaussian laser pulse in the mahnetized plasma have been investigated by semi-analytical and numerical methods. The influence of magnetic field has been studied on the evolution of the pulse length in plasma. It was indicated that the extent of self-compression increased with increasing the magnetic field.

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