Influence of Light Absorption on Relativistic Self-Focusing of Gaussian Laser Beam in Cold Quantum Plasma

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Abstract. When inter particle distance is comparable to the de Broglies wavelength of charged particles, quantum effects in plasmas are unavoidable. We have exploited an influence of light absorption on self-focusing of Gaussian laser beam in cold quantum plasma by considering relativistic nonlinearity. Nonlinear differential equation governing beam-width parameter has been established by using parabolic equation approach under paraxial and WKB approximations. The effect of light absorption on variation of beam-width parameter with dimensionless distance of propagation is presented graphically and discussed. It is found that light absorption plays vital role in weakening the relativistic self-focusing of laser beam during propagation in cold quantum plasma and gives reasonably interesting results.

INTRODUCTION

Laser-plasma interactions are perennially fraught with numerous nonlinear effects. As such this also spans the scope to many self-action effects. Phenomenon of self-focusing [1] is one of the important self-action effects that occur due to the laser induced changes in the dielectric properties of plasma. When an intense laser beam is shone into plasma, it changes its dielectric properties. The subsequent variation of the lights velocity across the beams wavefront causes them to bend in the medium that acts as a spherically converging lens, causing self-focusing of the laser beam [2]. In recent years, improving the laser self-focusing in plasmas has received the considerable attention due to their potential applications in diverse fields of laser-plasma interaction experiments. For these applications, it is desirable that the optical beam should propagate for extended distances without divergence and without being absorbed. In the last few decades most of the investigations on relativistic self-focusing of laser beams in plasmas have been directed within the framework of classical regime of laser-plasma interaction.

In the near future, quantum effects in plasmas tend to be unavoidable [3]. Recently, the increasing interest in studying quantum plasmas is due to their wide ranging applications [4] in nanotechnology, astrophysical and cosmological plasmas, fusion science, nonlinear quantum optics,, laser produced plasmas etc. Moreover, quantum plasmas are in the forefront of many intriguing questions around the frontiers of plasma science in general. Quantum effects in plasmas can be characterized by the thermal de Broglie wavelength, $\lambda_B = h/(m_e k_B T)^{1/2}$ of the particles composing the plasma which represents the spatial extension of a particles wave function, where h, m_e, k_B and T are Planck's constant, the electron mass, Boltzmann's constant and the plasma electron temperature, respectively. In classical regime, the de Broglie wavelength is so small that the separation between the particles is so large and the particles can be considered as point like. Subsequently, it is remarkable to postulate that quantum effects starts playing a significant role when the de Broglie wavelength is equal to or greater than the average inter-electron distance. It is well known that the quantum effects are also characterized by degeneracy and quantum coupling parameters [4].

Recently, the self-focusing of Gaussian laser beam in relativistic quantum plasmas [5, 6, 7] has been presented and reported that quantum effects can significantly enhance self-focusing relative to the classical relativistic [8] case of reference. An influence of density ramp on relativistic self-focusing in cold quantum plasmas has been extensively

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studied by Habibi and Ghamari [9]. Zare et al. [10] have also realized that in a dense plasma environment, the laser self-focusing occurs with the higher oscillation amplitude, smaller laser spot size and more oscillations during its propagation. It has been also reported [11, 12, 13] that combined effect of ponderomotive and relativistic self-focusing is important in laser beam propagation through the plasma. Kumar et al. [14] have presented the combined effect of relativistic and ponderomotive nonlinearity on self-focusing of Gaussian laser beam in a cold quantum plasma. Recently, it has been observed that light absorption plays vital role in self-focusing of laser beam in a plasma. [15, 16] We have also studied the effect of light absorption on relativistic [17] and relativistic-ponderomotive [18] self-focusing of Gaussian laser beam in plasma under classical relativistic case of reference.

It is important to notice that in previous contributions [5, 6, 9, 10, 14] of self-focusing of laser beam in quantum plasmas, light absorption was neglected. Therefore, we have shown contribution of light absorption in the present work to study relativistic self-focusing of Gaussian laser beam in cold quantum plasma. As usual, the present analysis employs the parabolic equation approach [1, 2] under the WKB and paraxial approximations.

SELF-FOCUSING

Consider the propagation of laser beam having Gaussian intensity distribution along its wavefront, through under-dense, unmagnitized, collisionless, cold quantum plasma of equilibrium electron density n_0

$$EE^* = E_0^2 exp\left(-\frac{r^2}{r_0^2}\right), \tag{1}$$

where, E_0 is the amplitude of Gaussian intensity distribution, r is the radial coordinate of cylindrical coordinate system and r_0 is the spot size of the laser beam at plane of incidence, i.e., at $z = 0$.

In the present case, we use the effective dielectric function for cold quantum plasma as [5]

$$\varepsilon = 1 - \frac{\Omega^2}{\gamma}\left(1 - \frac{\delta}{\gamma}\right), \tag{2}$$

where $\Omega = \omega_p/\omega$ is the Lorentz relativistic factor with $\alpha = e^2/m_0^2\omega^2c^2$ as the coefficient of relativistic nonlinearity, $\delta = 4\pi^4h^2/m_0^2\omega^2\lambda^4$ is the quantum contribution to the dielectric function for a cold plasma. Here e and m_0 are the charge and rest mass of electron; respectively, ω and λ are the frequency and wavelength of laser beam and c is the speed of light in free space.

From Eq.(2) it is clear that if $h = 0$ i.e., ignoring quantum effects, we can regain the classical relativistic dielectric function. Eq.(2) can also be written as [2]

$$\varepsilon = \varepsilon_0 + \Phi\left(EE^*\right) - i\varepsilon_i, \tag{3}$$

where ε_0 and Φ are the linear and nonlinear parts of the dielectric function respectively, ε_i takes care of absorption.

Under WKB approximation, the coupled equations in terms of eikonal S and intensity of laser beam A_0^2 can be written as

$$2\frac{\partial S}{\partial z} + \left(\frac{\partial S}{\partial r}\right)^2 = \frac{1}{k_0^2A_0}\nabla_\perp^2 A_0 + \frac{\Phi}{\varepsilon_0}A_0, \tag{4}$$

and

$$\frac{\partial A_0^2}{\partial z} + \frac{\partial A_0^2}{\partial r}\frac{\partial S}{\partial r} + A_0^2\left(\frac{\partial^2 S}{\partial r^2} + \frac{1}{r}\frac{\partial S}{\partial r} - k_0\frac{\varepsilon_i}{\varepsilon_0}\right) = 0. \tag{5}$$

The solution of Eqs.(4) and (5) satisfying the initial condition for intensity distribution of a Gaussian beam can be expressed as

$$S = \frac{r^2}{2f}\frac{df}{dz} + \phi(z), \tag{6}$$

and

$$A_0^2 = \frac{E_0^2}{f^2}exp\left(\frac{r^2}{r_0^2f^2} - 2K_iz\right), \tag{7}$$

where K_i is the absorption coefficient and $\phi(z)$ is the axial phase.

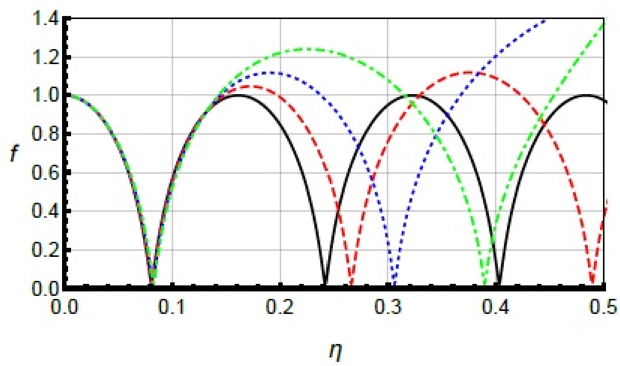

FIGURE 1. Variation of beam-width parameter f with dimensionless distance of propagation η for different values of normalized absorption coefficients $K_i^{'}$. Solid curve ($K_i^{'} = 0.0$), dashed curve ($K_i^{'} = 0.5$), dotted curve ($K_i^{'} = 1.0$), dot-dashed curve ($K_i^{'} = 1.5$). Laser-plasma parameters are; $n_0 = 4 \times 10^{19} cm^{-3}$, $r_0 = 20\mu m$, $\alpha E_0^2 = 0.1$, $\omega = 10^{19} rad/s$.

Following the paraxial approach given by Sodha et al. [2] the dimensionless beam-width parameter f is obtained as

$$\frac{d^2 f}{d\eta^2} = \frac{1}{f^3} - \rho_0^2 \frac{P_\eta}{f^3}\left(1 + \frac{P_\eta}{f^2}\right)^{-\frac{1}{2}}\left(\left(1 + \frac{P_\eta}{f^2}\right)^{\frac{1}{2}} - \delta\right)^{-2}, \tag{8}$$

where $P_\eta = \alpha E_0^2 exp\left(-2K_i^{'}\eta\right)$, $K_i^{'} = K_i R_d$ is the normalized absorption coefficient, $R_d = k_0 r_o^2$ is the Rayleigh length, $\rho_0 = r_0\omega_p/c$ is the normalized equilibrium beam radius. Eq.(8) can be solved numerically with appropriate boundary conditions.

RESULTS AND DISCUSSION

Equation (8) describes the variation of dimensionless beam-width parameter f with dimensionless distance of propagation η in cold quantum plasma. Analytical solution of this equation is not possible; hence, we seek numerical computation technique to solve this equation. This equation has been solved by using fourth order Runge-Kutta method for the laser-plasma parameters; $n_0 = 4 \times 10^{19} cm^{-3}$, $r_0 = 20\mu m$, $\alpha E_0^2 = 0.1$, $\omega = 10^{19} rad/s$ to analyze an influence of light absorption on self-focusing. Eq. (8) is solved by using boundary condition for an initially plane wavefront ($f = 1$, $df/d\eta = 0$ at $\eta = 0$). It is to be noted that in absence of light absorption effect ($K_i^{'}$), Eq. (8) reduces to Eq. (12) of our earlier result [5] for non-absorbing case of reference. Further, it is interesting to note that neglecting quantum effects (Setting $\delta = 0$), Eq.(8) reduces to Eq.(10) of our earlier result [17] for effect of light absorption on relativistic self-focusing of Gaussian laser beam in plasma.

The variation of f with η for four different values of normalized absorption coefficients $K_i^{'}$ ($K_i^{'} = 0.0, 0.5, 1.0, 1.5$) is displayed in Fig. 1. It is observed from this figure that in the absence of absorption, the laser beam is self-focused with stationary oscillatory mode as it propagates through the cold quantum plasma. Such stationary oscillatory self-focusing character of beam-width parameter has been reported in several earlier investigations [5, 6, 9, 10, 14] at different laser plasma parameters and situations of interaction. However, self-focusing of laser beam gets destroyed by taking into account the absorption. Subsequently, maximum of beam-width increases during the propagation in plasma. Finally the beam becomes too weak to control the diffraction and suffers steep steady divergence. As obvious, penetration decreases with increasing the absorption.

To further clarify the results for describing the variation of beam-width parameter with normalized distance of propagation in Fig. 1, we analyze the dependence of nonlinear dielectric function ϕ of the plasma in relativistic regime of interaction. Fig. 2 illustrates the dependence of with for same absorption coefficients ($K_i^{'} = 0.0, 0.5, 1.0, 1.5$) as shown in Fig. 1. This figure exhibits that ϕ oscillates with η and falls due to absorption. The oscillation peaks in ϕ corresponds to the valleys of f that represents focusing trend of f but damped earlier by increasing the laser absorption which is adverse for systems that needs the propagation of laser beam over several Rayleigh lengths where quantum contribution is important.

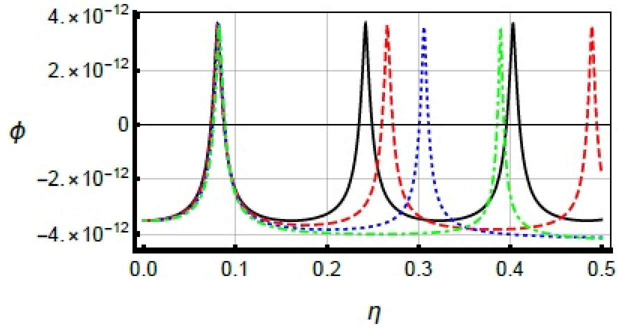

FIGURE 2. Variation of nonlinear dielectric function ϕ with dimensionless distance of propagation η for different values of normalized absorption coefficients K_i'. Solid curve ($K_i' = 0.0$), dashed curve ($K_i' = 0.5$), dotted curve ($K_i' = 1.0$), dot-dashed curve ($K_i' = 1.5$). Other numerical parameters are same as that of in figure 1.

In conclusion, following important conclusions are drawn from the present study:

- Weakening of self-focusing effect takes place with increase in laser absorption in relativistic cold quantum plasma.
- Laser absorption is unfavorable for its propagation in cold quantum plasma.

Our results may be helpful for many applications related to laser-plasma interaction requiring the propagation of laser beams to several Rayleigh lengths without being absorbed is requisite.

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