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Relativistic ponderomotive self-focusing of quadruple Gaussian laser beam in cold quantum plasma

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Research Article

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Abstract

In the present paper, we have investigated self-focusing of the quadruple Gaussian laser beam in underdense cold quantum plasma. The non-linearity chosen is associated with the relativistic mass effect that arises due to quiver motion of electron and electron density perturbation caused by ponderomotive force. The non-linearity modifies the plasma frequency in the dielectric function and hence the refractive index of the medium. The focusing/defocusing of the quadruple laser depends on the refractive index of the medium. We have set up non-linear differential equation that controls the beam width parameter by using well-known paraxial ray approximation and Wentzel–Krammers–Brillouin approximation. The effect of intensity parameter and electron temperature is observed on laser beam self-focusing in the presence of cold quantum plasma. From the results, it is revealed that electron temperature and the initial intensity of the laser beam control the profile dynamics of the laser beam.

Introduction

The interaction of intense laser pulses with plasmas has been studied extensively these days due to its rapidly growing interest in understanding a number of non-linear physical processes arising from the laser–plasma interactions. These processes are finite pulse effect, filamentation, self-phase modulation, second harmonic generation (Kant *et al.*, 2011), and self-focusing of laser/electromagnetic waves. The study of some of these physical process leads to the insight of laser–plasma interaction dynamics, keeping non-linear process at a low level. Much attention has been given to the study of self-focusing these days, due to its wide range of applications, such as inertial confinement fusion (ICF) (Tabak *et al.*, 1994; Regan *et al.*, 1999), ionospheric modification (Guzdar *et al.*, 1998; Gondarenko, 2005), and new radiation sources (Fedotov *et al.*, 2000). The success of these applications depends on the possibility of long distance propagation of intense laser beam in plasmas. The laser beam tends to diverge naturally due to diffraction effects, which is counterbalanced by the self-focusing of the laser beam led by nonlinear behavior of the medium. However, in the absence of nonlinearity, the beam will diverge appreciably in a Rayleigh length.

With the availability of intense laser pulses, relativistic self-focusing results due to the quiver motion of electrons. The oscillatory electron velocity reaches comparable to the velocity of light leading to reduced local plasma frequency. Another non-linear phenomena arises due to ponderomotive force-type non-linearity resulting in radiation pressure (Hora, 1969). Because of the immense pressure, the electrons are expelled from high field intensity to the lower field intensity region. This results in the modification of the density distribution of electrons in plasma, thereby developing density gradient. The combined effect of both (relativistic and ponderomotive) non-linearities thus affects the beam propagation and is well established both theoretically and experimentally by various researchers. These contributions are thus represented with a third-order non-linearity in the weakly relativistic limit in laser wave equation (Patil *et al.*, 2013). In a weakly relativistic ponderomotive (RP) plasma medium, the assumption $\tau \gg \tau_{pe} > T_0$ is valid, where τ is the laser pulse duration, τ_{pe} is the electron response time, and T_0 is the laser period. Since the ions are relatively heavier than electrons, the force acting on ion is neglected in the present investigation.

The above model for weakly relativistic ponderomotive regime has been studied extensively recently by various researchers using fundamental TEM_{00} mode Gaussian laser beam. Niknam *et al.* (2013) has recently studied the electron density distribution due to the effect of weakly relativistic ponderomotive force in the interaction of laser pulses with plasma. Patil *et al.* (2012) have studied the effect of weakly relativistic and ponderomotive self-focusing by choosing the appropriate experimental parameters and for laser power greater than critical power. They observed that the inclusion of ponderomotive term in relativistic term enhances beam focusing.

Self-focusing due to the combined effect of relativistic and ponderomotive non-linearities and its effect on modulation instability arising due to density perturbation have been studied by Jha *et al.* (2008). Further, density steepening occurring because of plasma inhomogeneity and plasma permittivity due to weakly relativistic and ponderomotive profile is studied by Niknam *et al.* in collisionless and collisional regimes (Niknam *et al.*, 2009). They have further derived modified dielectric constant for cold under dense plasma and investigate the profile of electric and magnetic field. The deviation of electromagnetic field profile from sinusoidal behavior is observed. Apart from taking Gaussian laser beam, a few studies have been attempted by considering non-Gaussian laser beams. In such an endeavor, Patil and Takale (2013*b*) have studied self-focusing of cosh-Gaussian (ChG) beams in plasma by taking weakly RP regime. The results obtained by them were in reasonable agreement with variational approach followed by Gill *et al.* (2011) and stronger self-focusing is observed in comparison with relativistic case. Kumar *et al.* (2016) have recently revisited the Patil *et al.*'s (2013) work by considering pinching effect of quantum plasma and by taking combined effect of both ponderomotive and relativistic non-linearity. The model established was successful in explaining the role of ponderomotive non-linearity in enhancing the beam focusing when the density of the plasma electrons becomes sufficiently very high.

Being a newly emerging field in plasma physics, quantum plasmas have gained increasing attention during the past few years (Ren *et al.*, 2007; Jung and Murakami, 2009; Hefferon *et al.*, 2010; Shukla and Eliassion, 2010). When the density of plasma electrons becomes very high, quantum effects start playing a vital role. Many investigations have been reported recently on the plasma systems where quantum effects are dominant and have relevance in a variety of applications viz cosmological and astrophysical systems (Jung, 2001; Opher *et al.*, 2001), laser-produced plasmas (Kremp *et al.*, 1999), laser–solid plasma interactions (Kremp *et al.*, 1999; Marklund and Shukla, 2006), etc. In almost all these applications, quantum effects are dominant due to high-density plasmas. The tendency of quantum plasma as a non-linear medium (Patil and Takale, 2013*a*, 2014; Habibi and Ghamari, 2014; Kumar *et al.*, 2016; Aggarwal *et al.*, 2017) has grown interest in all the practical situations, where de Broglie wavelength of charged particles is greater than or equal to the inter particle distance, therefore one cannot ignore the quantum nature of the plasma constituents.

However, in recent years, a number of theoretical investigations have been ventured by studying self-focusing of the laser beam in plasma considering Gaussian (Zhou *et al.*, 2011; Navare *et al.*, 2012; Patil and Takale, 2013*b*, 2014; Aggarwal *et al.*, 2016), cosh Gaussian (Patil *et al.*, 2009; Gill *et al.*, 2011; Patil *et al.*, 2012; Aggarwal *et al.*, 2014), Hermite Cosh Gaussian (Patil *et al.*, 2010; Nanda *et al.*, 2013; Kant and Nanda, 2014; Nanda and Kant, 2014; Wani and Kant, 2016; Wani *et al.*, 2018), elliptical Gaussian laser beam (Nayyar and Soni, 1978; Soni and Nayyar, 1980; Singh *et al.*, 2008; Singh and Walia, 2012), and multiple Gaussian laser beam (Sati *et al.*, 2012). In many applications, high-power densities at the target are required. So in an attempt to achieve it, there is the common practice of combining multiple laser beams. Mutual focusing/defocusing and cross-focusing of two laser beams have been studied by many coworkers in the past few years. However, combining four beams identically are mathematically easier than combining two beams. Self-focusing of the quadruple Gaussian laser beam comprising four coherent Gaussian laser beams has already been studied considering ponderomotive non-linearity (Sati *et al.*, 2012). Aggarwal *et al.* (2015*a*; 2015*b*) extended the above work and studied self-focusing of circularly polarized quadruple Gaussian laser beam in relativistic magnetized plasma. In their investigation, enhanced self-focusing is reported when laser beam propagates in extraordinary mode rather than in ordinary mode. In a similar investigation, self-focusing of the quadruple Gaussian laser beam is thoroughly studied in inhomogeneous magnetized plasma by considering linear absorption (Aggarwal *et al.*, 2015*a*, 2015*b*). Their observation shows that, the initial converging/diverging beam shows oscillatory convergence and divergence, respectively, and the beam is more focused at lower intensity rather than at higher intensities. However, no attempt had been made by researchers to enhance the self-focusing of the quadruple Gaussian beam using relativistic and ponderomotive regime in the presence of cold quantum plasma.

The paper is modeled as follow: In "Formalism" section, authors have developed the non-linear part of plasma permittivity by taking into account weakly RP non-linearity and by inclusion of cold quantum plasma. In "Self-focusing" section , authors have set up the non linear differential equation governing the propagation of quadruple Gaussian beam. Results are presented in "Numerical results and discussion" section.

Formalism

Consider quadruple Gaussian laser beam with angular frequency "ω" propagating in unmagnetized cold quantum plasma along the z direction in cylindrical coordinate system. The magnitude of electric field vector "**E**" of laser beam is given as

$$\mathbf{E} = \hat{x}A(x, y, z)\exp[i(\omega t - kz)], \tag{1}$$

where A is the amplitude of the laser field, $k = \omega\sqrt{\epsilon_o}/c$ is the wave propagation constant, ϵ_o is the dielectric constant of the medium on the axis, and c is the speed of light in free space.

The initial intensity distribution of the quadruple laser beam is given by (Sati *et al.*, 2012):

$$\begin{aligned} AA^{\star}|_{z=0} = (16)^2 A_{oo}^2 [&e^{-((x-x_o)^2+y^2)/2r_o^2} + e^{-((x+x_o)^2+y^2)/2r_o^2} \\ &+ e^{-(x^2+(y-x_o)^2)/2r_o^2} + e^{-(x^2+(y+x_o)^2)/2r_o^2}]^2, \end{aligned} \tag{2}$$

where $(-x_o, 0)$, $(x_o, 0)$, $(0, -x_o)$, and $(0, x_o)$ are the amplitude maxima of four identical coherent Gaussian beams comprising the quadruple beam. The intensity distribution of quadruple Gaussian beam for $z > 0$ in the paraxial ray approximation can be written in the following form:

$$\begin{aligned} AA^{\star} = \frac{(16)^2 A_{oo}^2}{f^2} [&e^{-((x-x_o f)^2+y^2)/2f^2r_o^2} + e^{-((x+x_o f)^2+y^2)/2f^2r_o^2} \\ &+ e^{-(x^2+(y-x_o f)^2)/2f^2r_o^2} + e^{-(x^2+(y+x_o f)^2)/2f^2r_o^2}]^2, \end{aligned} \tag{3}$$

where $16A_{oo}e^{-x_o^2/2r_o^2}$ is the laser amplitude and r_o is the initial half width of each beam segment wave.

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The effective dielectric permittivity ϵ for cold quantum plasma is of the following form (Jung and Murkami, 2009):

$$\epsilon = 1 - \frac{\omega_p^2}{\omega^2\gamma}\left(1 - \frac{\delta}{\gamma}\right)^{-1}\frac{n}{n_0}, \tag{4}$$

where $\gamma = (1 + \alpha|A|^2)^{1/2}$ is the relativistic factor with $\alpha = e^2/m^2c^2\omega^2$. Here, e and m are the electronic charge and rest mass, respectively. $\delta = 4\pi^4h^2/m^2\omega^2\lambda^4$ is a parameter which is associated with quantum wavelength of the species (λ) and, h is the planck constant. $\omega_p = (4\pi ne^2/m)^{1/2}$ is the plasma frequency and n is the electron density, which is modified by ponderomotive force in the steady state and is given by (Niknam *et al.*, 2009):

$$n = n_0 \exp\left(-\frac{mc^2}{T_e}(\gamma - 1)\right). \tag{5}$$

Here, T_e is the electron temperature in units of energy and n_0 is the maximum electron density where the laser electric field is zero. In Eq. (4), ϵ is a function of irradiance $\mathbf{EE}^\star$ of quadruple Gaussian beam, which is a function of r^2. In paraxial ray approximation, ϵ can be Taylor expanded in the radial direction around $r = 0$ as

$$\epsilon(r) = \epsilon_o - \frac{r^2}{r_o^2}\Phi, \tag{6}$$

where

$$\epsilon_o = 1 - \frac{\omega_{po}^2}{\omega^2\gamma_o}\left(1 - \frac{\delta}{\gamma_o}\right)^{-1}\exp\left(-\frac{mc^2}{T_e}(\gamma_o - 1)\right), \tag{7}$$

and

$$\phi = \frac{\omega_{po}^2}{(2\omega^2)}\frac{1}{f^3\gamma_0^3}\left(\frac{X}{f}\right)\left(-1 + \frac{x_o^2}{2r_o^2}\right)\left(1 - \frac{\delta}{\gamma_o}\right)^{-2} \times \left[1 + \frac{m_oc^2}{T_e}(\gamma_o - \delta)\right]\exp\left[-\frac{m_oc^2}{T_e}(\gamma_o - 1)\right], \tag{8}$$

where $\omega_{po} = (4\pi n_o e^2/m)^{1/2}$, $\gamma_o = (1 + X)^{1/2}$, and $X = (16^2\alpha A_{oo}^2 e^{(-x_o^2)/(r_o^2)}/f^2)$.

Self-focusing

The general form of non-linear wave equation governing the evolution of the electric field is obtained as

$$\frac{\partial^2 E}{\partial z^2} + \left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\right)E + \frac{\omega^2}{c^2}\epsilon E = 0. \tag{9}$$

The above equation can be obtained in the light of Maxwell's equations. The inequality $k^{-2}\nabla^2(\ln\epsilon) \ll 1$ is valid in almost all situations of practical interest. One can obtain quasioptic equation by putting $\mathbf{E}$ from Eq. (1) in Eq. (9), and using Wentzel–Krammers–Brillouin approximation. By neglecting $\partial^2\mathbf{A}/\partial z^2$ the resulting wave equation reduces to:

$$-2ik\frac{\partial A}{\partial z} + \left(\frac{\partial^2 A}{\partial x^2} + \frac{\partial^2 A}{\partial y^2}\right) - \frac{r^2}{r_0^2}\frac{\omega^2}{c^2}\phi A = 0. \tag{10}$$

We follow an approach given by Akhmanov *et al.* (1968) and further developed by Sodha *et al.* (1976). Hence introducing an eikonal as $A = A_o(r, z)\exp[-ikS(r, z)]$ in Eq. (10) and separating real and imaginary parts, one can obtain:

$$2\frac{\partial S}{\partial z} + \left[\left(\frac{\partial S}{\partial x}\right)^2 + \left(\frac{\partial S}{\partial y}\right)^2\right] = \left(\frac{\partial^2 A_o}{\partial x^2} + \frac{\partial^2 A_o}{\partial y^2}\right)\frac{1}{k^2A_o} + \frac{r^2}{r_0^2}\frac{\omega_p^2}{\omega^2}\frac{\phi}{\epsilon_o}, \tag{11}$$

$$\frac{\partial A_o^2}{\partial z} + \left[\frac{\partial A_o^2}{\partial x}\frac{\partial S}{\partial x} + \frac{\partial A_o^2}{\partial y}\frac{\partial S}{\partial y}\right] + A_o^2\left[\frac{\partial^2 S}{\partial x^2} + \frac{\partial^2 S}{\partial y^2}\right] = 0. \tag{12}$$

Here, $A_o(r, z)$ and $S(r, z)$ are real functions of space variables. The solution of Eqs (11) and (12) can be written as

$$A_o^2 = \frac{(16)^2A_{oo}^2}{f^2}e^{-x_o^2/r_o^2}e^{-r^2/f^2r_o^2}\left(1 + \frac{r^2x_o^2}{4r_o^4f^2} + \frac{(x^4 + y^4)x_o^4}{48r_o^8f^4}\right)^2, \tag{13}$$

and

$$S = S_o + \frac{1}{f}\frac{df}{dz}\left(\frac{x^2}{2} + \frac{y^2}{2}\right). \tag{14}$$

Differentiating Eq. (14) w.r.t. x, y, z and substituting in Eq. (11), we get

$$2\frac{\partial S_o}{\partial z} + \frac{r^2}{f}\frac{d^2f}{dz^2} = \left(\frac{\partial^2 A_o}{\partial x^2} + \frac{\partial^2 A_o}{\partial y^2}\right)\frac{1}{k^2A_o} + \frac{r^2}{r_0^2}\frac{\omega_p^2}{\omega^2}\frac{\phi}{\epsilon_o}, \tag{15}$$

where

$$\left(\frac{\partial^2 A_o}{\partial x^2} + \frac{\partial^2 A_o}{\partial y^2}\right)\frac{1}{A_o} = \frac{-2}{r_o^2f^2}\left(1 - \frac{x_o^2}{2r_o^2}\right) + \frac{r^2}{r_o^4f^4}\left(1 - \frac{x_o^2}{r_o^2}\right). \tag{16}$$

By substituting Eqs (8) and (13) in Eq. (15) and equating the coefficient of r^2 on both sides, one can obtain the equation of self-focusing of quadruple Gaussian beam in relativistic and ponderomotive regime as given below:

$$\frac{d^2f}{d\zeta^2} = \frac{1}{f^3}\left(1 - \frac{x_o^2}{r_o^2}\right) - \frac{1}{2}\left(\frac{\omega_p r_0}{c}\right)^2\frac{1}{f^2\gamma_0^3}\left(\frac{X}{f}\right) \times \left(-1 + \frac{x_o^2}{2r_o^2}\right)\left(1 - \frac{\delta}{\gamma_o}\right)^{-2}\left[1 + \frac{m_oc^2}{T_e}(\gamma_o - \delta)\right] \times \exp\left[-\frac{m_oc^2}{T_e}(\gamma_o - 1)\right]. \tag{17}$$

Here $\zeta = z/kr_o^2$ is dimensionless distance of propagation. On r.h.s of Eq. (17), the first term (diffraction term) responsible for diffractional divergence of the beam and the second term (nonlinear term), leads to the relativistic and ponderomotive self-focusing determining the propagation character of the beam. Equation (17) is solved using suitable laser and plasma parameters and for an initial plane wave front i.e. for $(df/d\zeta) = 0$ and $f = 1$ at $\zeta = 0$. The propagation characteristic of quadruple Gaussian beam could be determined without convergence or divergence for the condition $(d^2f/d\zeta^2) = 0$, i.e., in the self-trapped mode. Using $(d^2f/d\zeta^2) = 0$, in Eq. (17), one can obtain a relation between inverse of square of equilibrium beam radius $\rho_o = r_o\omega_p/c$ and critical intensity of the beam $\Pi_o^2 = \alpha A_{oo}^2$. The expression after simplification can be written as:

$$\frac{1}{\rho_o^2} = \frac{X_1(1+X_1)^{-3/2}\left(-1+\frac{x_o^2}{2r_o^2}\right)\left[1+\frac{m_o c^2}{T_e}(1+X_1)^{-\frac{1}{2}}-\delta\right] \exp\left[-\frac{m_o c^2}{T_e}\left((1+X_1)^{\frac{1}{2}}-1\right)\right]\left(1-\delta(1+X_1)^{-\frac{1}{2}}\right)^{-2}}{2\left(1-\frac{x_o^2}{2r_o^2}\right)}. \tag{18}$$

Here, $X_1 = 256\alpha A_{oo}^2 e^{(-x_o^2)/(r_o^2)}$.

Numerical results and discussion

In the present section, we will discuss the self-focusing of quadruple Gaussian laser beam in cold quantum plasma. Equation (17) is the fundamental second-order non-linear differential equation governing the beam width parameter as a function of normalized distance of propagation ζ. The analytical solution of Eq. (17) is not possible; therefore, we seek the help of numerical computation to investigate the evolution of beam dynamics. There are several terms on the r.h.s of Eq. (17) and the fate of the laser beam depends on various parameters such as lateral separation (x_0/r_0), electron temperature (T_e), cold quantum parameter (δ), and relativistic factor (γ). All these parameters play a vital role in contributing to the dynamics of the laser beam for the following set of parameters chosen: $\omega_o = 1.778 \times 10^{20}$rad/s, $r_o = 0.001$ cm, $\lambda = 0.0106$ nm, $n_o = 1.0 \times 10^{19}/\text{cm}^3$, intensity $= 5.45 \times 10^{26}\text{W/cm}^2$, $\omega_c/\omega_o = 0.1–0.5$, and $T_e = 15$ KeV.

Figure 1 depicts the graph for the variation of non-linear plasma permittivity ϕ as a function of intensity and for fixed value of lateral separation parameter $(x_0/r_0 = 0.6)$. The non-linearity is an increasing function of intensity up to intensity $= 5.45 \times 10^{26}$ W/cm^2 thereby leading to reduced focusing length of the beam. The plasma permittivity is found to fall rapidly after achieving maximum. Since plasma permittivity is also a function of temperature, so we have elaborated our results and plotted the variation of plasma permittivity ϕ as a function of electron temperature.

Figure 2 represents the variation of non-linear plasma permittivity ϕ as a function of electron temperature. It is clear from the graph that the non-linearity in case of relativistic ponderomotive cold quantum plasma (RPCQ) is stronger than RP plasma as the non-linearity saturates more for RPCQ than RP case of reference. This is due to the fact that the effect of ponderomotive non-linearity assists the relativistic effects and results in stronger self-focusing. The electron temperature for which maxima is attained in case of RPCQ is 15 KeV. Therefore, strongest self-focusing is achieved at $T_e = 15$ KeV as elucidated from Figure 5. The electron temperature is optimized to ensure stronger self-focusing as the laser propagation takes place in denser plasmas.

Figure 3 depicts the variation of plasma permittivity ϕ as a function of intensity in case of RPCQ and RP plasma for fixed value of lateral separation parameter $(x_0/r_0 = 0.6)$. The plasma permittivity increases with intensity and achieves maximum and thereafter it falls rapidly. The behavior is similar in both cases of RPCQ and RP plasma models. The maximum achieved in case of RPCQ is appreciably larger than RP plasma model for the same set of laser and plasma parameter chosen. Thus, there is a wide range of laser intensities that can be focused in case of RPCQ plasma in comparison with RP plasma.

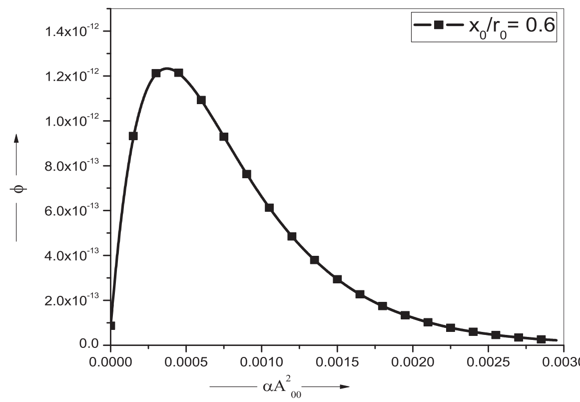

Fig. 1. Variation of non-linear plasma permittivity ϕ with intensity parameter in case of RPCQ plasma for $x_0/r_0 = 0.6$ and other parameters are as follow: $r_0 = 0.001$ cm, $\lambda = 0.0106$ nm, $n_o = 1.0 \times 10^{19}/\text{cm}^3$, and $T_e = 15$ KeV.

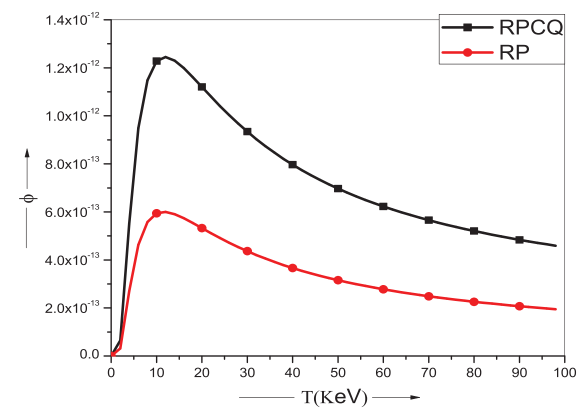

Fig. 2. Variation of non-linear plasma permittivity ϕ with electron temperature for two types of plasma model RPCQ and RP and for $x_0/r_0 = 0.6$. The other parameters being same as mentioned in caption of Figure 1.

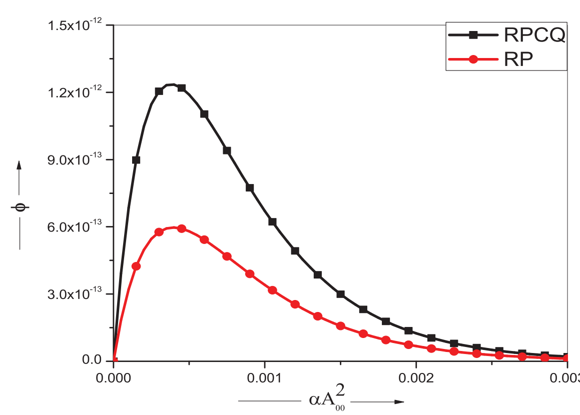

Fig. 3. Variation of nonlinear plasma permittivity ϕ with intensity parameter for two types of plasma model RPCQ and RP for $x_0/r_0 = 0.6$. The other parameters being same as mentioned in caption of Figure 1.

Figure 4 depicts the variation of beam width parameter (f) as a function of normalized distance of propagation (ζ) at different value of intensity parameter. The focusing is observed to be strongest in the case of intensity parameter $\alpha A_{00}^2 = 0.00025$. Further, self-focusing decreases with increase in intensity parameter

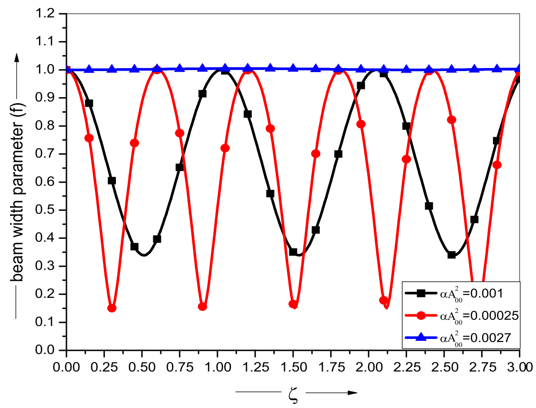

Fig. 4. Variation of beam width parameter f with normalized propagation distance ζ for relativistic ponderomotive cold quantum plasma (RPCQ) for different values of intensity parameter $\alpha A_{00}^2 = 0.001, 0.00025, 0.0027$. The other parameters are same as in Figure 1.

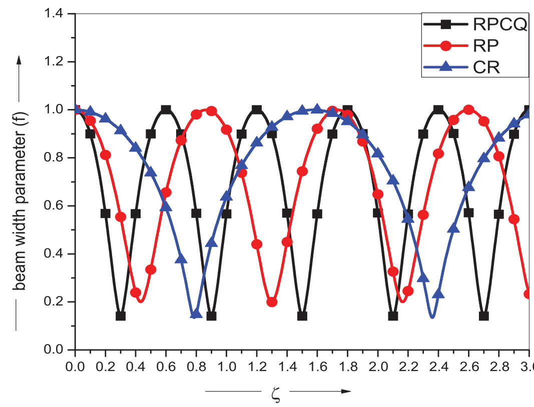

Fig. 6. Variation of beam width parameter f with normalized propagation distance ζ for relativistic ponderomotive cold quantum plasma (RPCQ), relativistic ponderomotive plasma (RP), and for classical relativistic (CR) case. The other parameters are same as in Figure 1.

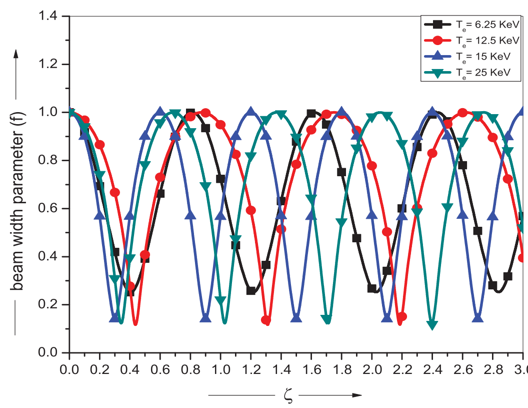

Fig. 5. Variation of beam width parameter f with normalized propagation distance ζ for relativistic ponderomotive cold quantum plasma (RPCQ) and for different value of electron temperature $T_e = 6.25$, 12.5, 15 and 25 KeV. The other parameters are same as in Figure 1.

beyond the $\alpha A_{00}^2 = 0.00025$. The self-trapping is observed to occur at $\alpha A_{00}^2 = 0.0027$. Thus, the beam propagates without convergence and divergence up to many Rayleigh lengths in the self-trapped mode, which is a key feature to the success of ICF and depends critically on long distance propagation of laser pulses at relativistic intensities ($>10^{18}$ W/cm^2).

We have further plotted the variation of beam width parameter (f) as a function of normalized distance of propagation (ζ) for different values of electron temperature $T_e = 6.5$, 12.5, 15, and 25 KeV as shown in Figure 5. The self-focusing is found to be strongest in case of $T_e = 15$ KeV as elucidated from Figure 5, for which the plasma permittivity is maximum as observed in Figure 2. As we increase the electron temperature beyond 15 KeV, the self-focusing starts weakening with increasing focusing length. This is due to the fact that the non-linear term is sensitive to the electron temperature T_e and relativistic factor γ, which further control the profile dynamics of the laser beam. A similar behavior is observed by Aggarwal *et al.* (2016), Wang and Zhou (2011), and Milani *et al.* (2014).

Figure 6 presents the variation of beam width parameter (f) as a function of normalized distance of propagation (ζ) for different types of plasma model, i.e., RPCQ, RP, and CR plasma. It is evident from the figure that strongest self-focusing is achieved for the RPCQ plasma model in comparison with those of RP plasma and classical relativistic (CR) case of reference. It is further concluded that quantum plasma acts as a non-linear medium and offered strongest self-focusing, thus acting as a catalyst in RP plasma. As a result, the laser beam is focused faster in quantum plasma and such a contribution of additional self-focusing is missing in RP and CR cases. Thus, self-focusing ability of laser beam in quantum plasma is better than both RP and CR case. These results are in agreement with the observation made by Aggarwal *et al.* (2017). The present investigation is helpful to the researchers to choose various laser and plasma parameters for enhancement in beam-focusing ability.

Conclusion

In the present investigation, authors have investigated the self-focusing of quadruple Gaussian laser beam in weakly relativistic cold quantum plasma. Following conclusions are drawn:

1. Self-trapping of the quadruple beam is observed up to several Rayleigh lengths for the optimized set of laser and plasma parameters.
2. As quantum plasma acts as a non-linear medium, the strongest self-focusing is observed in case of RPCQ plasma in comparison with RP plasma and CR case of reference.
3. The beam width parameter of the laser beam is controlled by the initial intensity of the laser beam and electron temperature.

Our investigation may be useful in understanding the physics of high-power laser-driven fusion and in the fast ignition of modern ICF experiments, where the mechanism of laser propagation in the quantum plasma is important and quantum effects are dominant.

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