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# Effects of plasma electron temperature and magnetic field on the propagation dynamics of Gaussian laser beam in weakly relativistic cold quantum plasma

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**Abstract**

Self-focusing of Gaussian laser beam has been investigated in quantum plasma under the effect of applied axial magnetic field. The nonlinear differential equation has been derived for studying the variations in the beam-width parameter. The effect of initial plasma electron temperature and the axial magnetic field on self-focusing and normalized intensity are studied. Our investigation reveals that normalized intensity increases to tenfolds where quantum effects are dominant. The normalized intensity further increases to twelvefolds on increasing the magnetic field.

## Introduction

Theoretical and experimental studies on the propagation characteristics of high-intensity electromagnetic beam in a nonlinear medium have been an interesting and fascinating field of research since decades. The nonlinear interaction of laser beam with plasma gives rise to many applications like ionospheric modification (Gondarenko, 2005; Sodha and Sharma, 2008), particle accelerator (Leemans *et al.*, 2006; Gonsalves *et al.*, 2011), inertial confinement fusion (Tabak *et al.*, 1994; Roth *et al.*, 2001; Betti and Hurricane, 2016), and high-harmonic generation (Kant *et al.*, 2011; Zhang and Thomas, 2015). The success of these applications is constrained to longer propagation distance of the electromagnetic beam through the nonlinear media with minimal loss in its intensity. When a laser pulse propagates through the plasma, it tends to change the refractive index of the plasma medium and results in many nonlinear effects and instabilities such as self-focusing and self-phase modulation of the laser beam, high-harmonic generation, filamentation instability, and group-velocity dispersion. Self-focusing is an important nonlinear process among others and is widely studied and discussed. In the self-focusing process, the refractive index of the medium changes due to the difference in intensity of the incoming electromagnetic beam between its on-axis and off-axis of the beam. The nonlinearities responsible for the self-focusing of the beam are relativistic, ponderomotive, and collisional type.

Beside these nonlinearities, the dielectric constant of the nonlinear medium is also affected by electron plasma temperature ($T_e$) which is independent of electric field of the incoming electromagnetic wave. Various studies can be found based upon plasma temperature effects on studying self-focusing properties of laser beam in the light of above-said nonlinearity (Gupta *et al.*, 2013; Niknam *et al.*, 2013; Varaki and Jafari, 2017; Walia *et al.*, 2017; Kumar and Aggarwal, 2018). Malik and Aria (2010) investigated the interaction of microwave radiations with the plasma medium while taking into account the ponderomotive nonlinearity and plasma temperature variations. They observed that plasma temperature helps in increasing ponderomotive nonlinearity through density perturbation and hence self-focusing of the beam can be enhanced. Wang and Zhou (2011) have rigorously studied the plasma temperature effects on the propagation characteristics of Gaussian laser beams in collisionless cold plasma with ponderomotive nonlinearity. In their investigations, they obtained four plasma temperature regions, namely oscillatory divergence, self-trapping, self-focusing and steady-divergence, which determine the propagation characteristics of Gaussian laser beam. Ping and Lin (2012) studied the effect of higher-order axial electron temperature on self-focusing behavior of the electromagnetic beam in collisional plasma. They observed that higher-order axial electron temperature tends to decrease the effect of collisional nonlinearity unlike lower-order terms of plasma temperature which assist the nonlinearity. Hence, different trends in self-focusing of the beam are observed. Milani *et al.* (2014) took different temperature ranges to study self-focusing of Gaussian beam through plasma and observed that at higher temperatures the beam divergence increases. This occurs because at higher temperature, the amplitude of beam-width increases to larger extent while frequency kept on decreasing and hence beam divergence increases. Patil *et al.* (2018) discussed self-focusing under the combined effects of light absorption and plasma temperature and observed that absorption coefficient helps to improve the self-focusing process with in a given range of temperatures. Recently, Ouahid *et al.* (2018) studied the light absorption parameter and plasma temperature effects on the self-focusing property of finite Airy–Gaussian beams in a relativistic–ponderomotive plasma regime. They studied the effects of different controlling parameters like absorption coefficient, plasma intensity and electron temperature.

With the passage of time, various authors studied the effects of magnetic field on the self-focusing property of Gaussian laser beam. When the magnetic field is applied parallel to the direction of the propagation of laser beam, the electrons get rotated in the direction of magnetic field lines, thereby improving the natural oscillating frequency of the electrons. This phenomena also changes the density distribution of electrons in comparison with the unmagnetized collisionless plasma as studied by Darian *et al.* (2016). Sharma *et al.* (2008) investigated the self-focusing and defocusing regions for Gaussian electromagnetic beam using kinetic theory approach in magnetized plasma.

Recently, quantum effects are gaining interest in the studies of self-focusing properties of the electromagnetic beam, as they have several applications in astrophysical system (Opher *et al.*, 2001; Benvenuto and De Vito, 2005; Harding and Lai, 2006), biophotonics (Barens *et al.*, 2003), neutron star (Chabrier *et al.*, 2002), ultra-cold plasmas (Killian, 2006), ultra-small electronic devices (Markowich *et al.*, 1990), quantum well (Ang *et al.*, 2006), and quantum dots (Ang and Zhang, 2007). Quantum plasmas are characterized as low temperature and high-density plasma medium and can be differentiated from classical plasma by the parameter $\chi = T_f/T_e$, where $T_f$ and $T_e$ are Fermi and plasma temperatures, respectively. We can define Fermi temperature and Fermi energy by the following relation (Landau and Lifshitz, 1980):

$$k_B T_f = E_f = \frac{\hbar^2}{2m_e}(3\pi^2 n_e)^{2/3} \tag{1}$$

$$\chi = \frac{T_f}{T_e} = \frac{1}{2}(3\pi^2)^{2/3}(n_e \lambda_B^3)^{2/3} \tag{2}$$

where $\lambda_B$ is the de-Broglie wavelength. When ($T_e \le T_f$), i.e. when plasma temperature is less than or equal to the Fermi temperature, then the system shifts from Maxwell–Boltzmann to Fermi–Dirac statistics and quantum effects starts dominating over the classical case. Alternatively, when de-Broglie wavelength becomes greater than or equal to interparticle distance ($n_e \lambda_B^3 \ge 1$), then quantum effects are more effective over the classical case. Several authors have studied the self-focusing properties of laser beam in quantum plasma (Patil *et al.*, 2013; Zare *et al.*, 2015; Kumar *et al.*, 2016; Aggarwal *et al.*, 2017*a*, 2017*b*; Mahajan *et al.*, 2018). Aggarwal *et al.* (2017*a*) have studied the self-focusing property of Gaussian laser beam propagating in weakly relativistic magnetized cold quantum plasma (WRMCQ) and observed the enhanced self-focusing under the combined effects of quantum conditions and magnetic field as compared with their individual cases.

In the present paper, we have studied the role of plasma electron temperature in the presence of applied magnetic field on the self-focusing properties of the Gaussian laser beam propagating in cold quantum plasma. To the best of our knowledge, the effect of plasma electron temperature on the normalized intensity in the presence of cold quantum plasma have not been studied so far. The paper is organized in four sections: The theoretical calculations for obtaining nonlinear plasma permittivity are carried out in the Formalism and Self-focusing sections. Numerical simulations and results are obtained in the Numerical results and discussion section and discussed thereafter. Further, the conclusions are presented in the last section.

## Formalism

Consider the linearly polarized high intense Gaussian laser beam propagating with angular frequency "$\omega_0$" along the $z$-axis through the magnetized cold quantum plasma. The electric field amplitude of the electromagnetic beam is given by

$$E(r,z) = A(r,z)\exp\left[-\iota(\omega_0 t - kz)\right] \tag{3}$$

where $A^2|_{z=0} = A_{oo}^2 \exp(-r^2/r_0^2)$ is the intensity of the laser beam, $r_0$ is the initial spot size, and $A_{oo}$ is the initial amplitude of the beam at $z = 0$. The wave number is given by $k = (\omega_0/c)\sqrt{\epsilon_o}$, $c$ is the speed of light in the vacuum, and $\epsilon_0$ is the axial dielectric function along the central position $z = 0$. The intensity distribution $A^2(r,z)$ for $z > 0$ is given by the following equation:

$$A^2(r,z) = \frac{A_{oo}^2}{f^2}\exp\left[-\frac{r^2}{r_0^2 f^2}\right] \tag{4}$$

The modified plasma electron density distribution $n_e$, which is the function of plasma electron temperature, is given by Niknam *et al.* (2009):

$$n_e = n_0 \exp\left[-\frac{m_e c^2}{T_e}(\gamma - 1)\right] \tag{5}$$

where $n_0$ is the unperturbed plasma electron density, $m_e$ is the mass of the electron, and $T_e$ is the plasma electron temperature in the units of energy. $\gamma$ is the Lorentz relativistic factor obtained iteratively for ($\omega_c/\gamma\omega_0$) < 1 as given by Pandey and Tripathi (2009) and Gill *et al.* (2010):

$$\gamma = \left[1 + A^2 + 2A^2\left(\frac{\omega_c}{\omega_0}\right)\left(\frac{1}{\sqrt{1+A^2}}\right) + 3A^2\left(\frac{\omega_c}{\omega_0}\right)^2\left(\frac{1}{1+A^2}\right)\right]^{1/2} \tag{6}$$

In the present model, we are investigating the beam propagation characteristics in weakly relativistic magnetized cold quantum (WRMCQ) plasma. Since the quiver velocity of electrons is much more than their thermal velocities; hence, we can assume that the plasma behavior is cold.

The dielectric function $\epsilon$ here is of a second-rank tensor $\epsilon_{ij}$ and takes the simple form when the magnetic field is directed along one of the Cartesian co-ordinate axes. Therefore, the

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magnetic field is along the direction of wave propagation, i.e. along the z-axis. In this case, $\epsilon_{ij}$ has only three nonvanishing components, namely $\epsilon_{xx} = \epsilon_{yy}$, $\epsilon_{xy} = -\epsilon_{yx}$, and $\epsilon_{zz}$ with $\epsilon_{xz} = \epsilon_{zx} = \epsilon_{yz} = \epsilon_{zy} = 0$ (Sharma *et al.*, 2008). The general form of dielectric permittivity can be written as follows:

$$\epsilon = \epsilon_{xx} - i\epsilon_{xy} = \epsilon_0 + \epsilon_r(\mathrm{EE}^*) \tag{7}$$

where $\epsilon_0$ and $\epsilon_r(\mathrm{EE}^*)$ are the linear and nonlinear part of the plasma dielectric function.

$$\epsilon_{zz} = \epsilon_{ozz} + \phi \tag{8}$$

where $\epsilon_{ozz} = 1 - (1/\gamma)(\omega_p^2/\omega_0^2)$ and $\phi = (1/\gamma)(\omega_p^2/\omega_0^2)$. Where $\epsilon_0 = 1 - \omega_p^2/\omega_0^2$ and $\omega_p = \sqrt{4\pi n_0 e^2}/m_e$ is the plasma frequency. The nonlinear plasma dielectric function in WRMCQ plasma can be written as

$$\epsilon_r(\mathrm{EE}^*) = \frac{\omega_p^2}{\omega_0^2}\left[1 - \frac{n_e}{n_0}\frac{1}{\gamma}\left(1 - \frac{\delta}{\gamma}\right)^{-1}\right] \tag{9}$$

Expanding $\epsilon_r$ using paraxial ray approximation and Taylor's series expansion around $r = 0$ and retaining the terms up to second power of $r^2$, we get the nonlinear plasma permittivity as given below

$$\epsilon(r,z) = \epsilon_r(r = 0) = \epsilon_0(z) - \frac{r^2}{r_0^2}\Phi \tag{10}$$

where $\epsilon_0(z)$ is the plasma permittivity, which corresponds to the maximum electric field on the axis:

$$\epsilon_0(z) = 1 - \frac{\omega_p^2}{\omega_0^2}\frac{1}{\gamma_0}\exp\left[-\frac{m_e c^2}{T_e}(\gamma_0 - 1)\right]\left(1 - \frac{\delta}{\gamma_0}\right)^{-1}, \tag{11}$$

and $\Phi$ is the nonlinear plasma permittivity, which is calculated as

$$\begin{aligned}\Phi = {}& \frac{A_{oo}^2}{2f^4}\frac{\omega_p^2}{\omega_0^2}\frac{1}{\gamma_0^3}\exp\left[-\frac{m_e c^2}{T_e}(\gamma_0 - 1)\right]\left(1 - \frac{\delta}{\gamma_0}\right)^{-2}\left[1 + \frac{m_e c^2\gamma_0}{T_e}\left(1 - \frac{\delta}{\gamma_0}\right)\right] \\ & \times\left[1 + \frac{\omega_c}{\omega_0}\frac{1}{\sqrt{1 + \frac{A_{oo}^2}{f^2}}}\left(2 - \frac{\frac{A_{oo}^2}{f^2}}{1 + \frac{A_{oo}^2}{f^2}}\right) + 3\frac{1}{1 + \frac{A_{oo}^2}{f^2}}\left(\frac{\omega_c}{\omega_0}\right)^2\left(1 - \frac{\frac{A_{oo}^2}{f^2}}{1 + \frac{A_{oo}^2}{f^2}}\right)\right]\end{aligned} \tag{12}$$

here $\gamma_0$ is the relativistic factor defined at $r = 0$ and can be written given by

$$\gamma_0 = \left[1 + \frac{A_{oo}^2}{f^2} + 2\frac{A_{oo}^2}{f^2}\left(\frac{\omega_c}{\omega_0}\right)\left(\frac{1}{\sqrt{1 + \frac{A_{oo}^2}{f^2}}}\right) + 3\frac{A_{oo}^2}{f^2}\left(\frac{\omega_c}{\omega_0}\right)^2\left(\frac{1}{1 + \frac{A_{oo}^2}{f^2}}\right)\right]^{1/2}. \tag{13}$$

## Self-focusing

To obtain the equation governing self-focusing of the electromagnetic beam, we use the Maxwell's equation and arriving at the nonlinear wave equation which satisfies the amplitude of Gaussian beam as follow

$$\frac{\partial^2 \mathbf{E}}{\partial z^2} + \alpha\nabla_\perp^2\mathbf{E} + \frac{\omega_0^2}{c^2}\epsilon\mathbf{E} = 0. \tag{14}$$

The quasioptic equation governing the evolution of electric field of laser beam through the plasma medium can be obtained under Wentzel–Kramers–Brilluion (WKB) and slowly varying envelope approximation as

$$-2\iota k\frac{\partial A}{\partial z} + \alpha\nabla_\perp^2 A - \frac{r^2}{r_0^2}\frac{\omega_0^2}{c^2}\epsilon A = 0, \tag{15}$$

where $\alpha = (1/2)(1 + \epsilon_0/\epsilon_{ozz})$ and $\epsilon_{ozz} = 1 - (1/\gamma_o)(\omega_p/\omega_0)^2$.

The solution of above the equation can be expressed in the form of complex amplitude $A(r,z)$ and following the approach given by Akhmanov *et al.* (1968) and Sodha *et al.* (1976) as follows:

$$A(r,z) = A_0(r,z)\exp\left[-\iota k(z)S(r,z)\right] \tag{16}$$

The envelope $A(r,z)$ includes real amplitude and complex phase terms which are functions of $z$ and $r$. Substituting the value of $A(r,z)$ from Eq. (16) into Eq. (15) to obtain two separate coupled equations of real and imaginary parts given below

$$2\frac{\partial S}{\partial z} + \left(\frac{\partial S}{\partial r}\right)^2 - \frac{\alpha}{k^2 A_0}\left(\frac{\partial^2 A_0}{\partial r^2} + \frac{1}{r}\frac{\partial A_0}{\partial r}\right) + \frac{r^2}{r_0^2}\frac{\epsilon_r}{\epsilon_0} = 0 \tag{17}$$

and

$$\frac{\partial A_0^2}{\partial z} + \frac{\partial S}{\partial r}\frac{\partial A_0^2}{\partial r} + \alpha A_0^2\left(\frac{\partial^2 S}{\partial r^2} + \frac{1}{r}\frac{\partial S}{\partial r}\right) = 0 \tag{18}$$

Expanding eikonal $S(r,z)$ as

$$S(r,z) = \frac{r^2}{2}\beta_0(z) + S_0(z) \tag{19}$$

where $\beta_0(z) = (1/f)(1/(1 + \epsilon_0/\epsilon_{ozz}))(df/dz)$ is the radius of curvature of the beam, and $S_0(z)$ is a constant related to the phase. Further, in order to obtain the equation of the dimensionless

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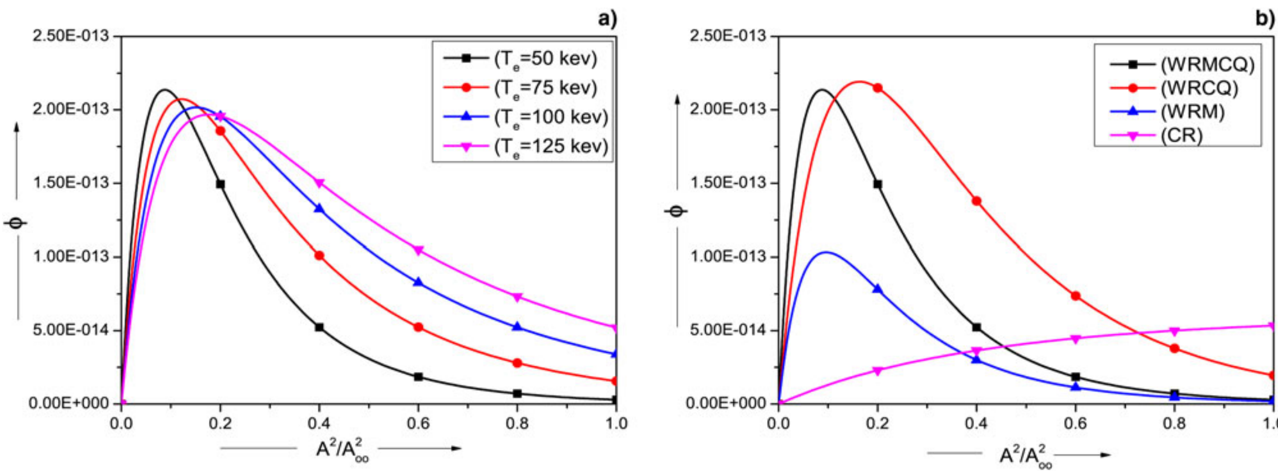


**Fig. 1.** (a) The plot of nonlinearity (Φ) versus normalized laser intensity ($A^2/A^2_{oo}$) for different plasma electron temperature $T_e$ values in WRMCQ plasma for the fixed value of magnetic field $\omega_c/\omega_0 = 0.3$. The other parameters are $\omega_0 = 1.778\times10^{20}$ rad/s, $r_0 = 0.003$ cm, $\lambda = 0.0106$ nm, and $n_0 = 3.14\times10^{18}$ cm$^{-3}$. (b) The plot between (Φ) and ($A^2/A^2_{oo}$) for WRMCQ, WRCQ, WRM, and CR cases of references at $T_e = 50$ keV. The other parameters are same as mentioned in (a).

beam-width parameter $f$, we substitute $A_0^2(=A^2)$ and $S(r,z)$ from Eqs (4) and (19), respectively, in Eq. (17). Equating the coefficients of $r^2$ on both sides of the resulting equation and normalizing by using $\xi = z/R_d$, where $R_d = kr_0^2$. The dimensionless beam-width parameter equation is derived and given by the following expression

$$\frac{d^2f}{d\xi^2} = \frac{\alpha^2}{f^3} - \frac{\alpha R_d^2}{\epsilon_0} f * \frac{A_{oo}^2}{2f^4}\frac{\omega_p^2}{\omega_0^2}\frac{1}{\gamma_0^3}\exp\left[-\frac{m_e c^2}{T_e}(\gamma_0-1)\right]\left(1-\frac{\delta}{\gamma_0}\right)^{-2}\left[1+\frac{m_e c^2\gamma_0}{T_e}\left(1-\frac{\delta}{\gamma_0}\right)\right]$$
$$\times\left[1+\frac{\omega_c}{\omega_0}\frac{1}{\sqrt{1+\frac{A_{oo}^2}{f^2}}}\left(2-\frac{\frac{A_{oo}^2}{f^2}}{1+\frac{A_{oo}^2}{f^2}}\right)+3\frac{1}{1+\frac{A_{oo}^2}{f^2}}\left(\frac{\omega_c}{\omega_0}\right)^2\left(1-\frac{\frac{A_{oo}^2}{f^2}}{1+\frac{A_{oo}^2}{f^2}}\right)\right] \quad (20)$$

From the curves, we can see that the nonlinearity responsible for self-focusing saturates earlier at temperature $T_e = 50$ keV as compared with $T_e = 75$, 100, and 125 keV. The nonlinearity thereafter falls rapidly with normalized intensity. Thus, plasma temperature plays a vital role in increasing the nonlinearity of the medium. It is further observed that with the increase in plasma electron temperature, the nonlinearity achieves lesser saturation. This is due to fact that as the temperature increases, the electron oscillations increases to larger extent and electrons are expelled away from the laser beam axis. This leads to the decrease in oscillatory frequency of the beam. Hence, the dielectric permittivity decreases with the plasma electron temperature. Thus, self-focusing is achieved with delayed focusing length at higher temperature due to redistribution in electron density which changes the effective dielectric constant of the medium. Figure 1b shows the plot between Φ and $A/A_{oo}^2$ but for different nonlinearities, namely WRMCQ plasma, weakly relativistic cold quantum (WRCQ), weakly relativistic magnetized (WRM), and classical relativistic (CR) plasma. The plasma electron temperature $T_e$ is fixed at 50 keV. The nonlinearity saturates earlier for WRMCQ plasma than for WRCQ, WRM, and CR cases of references, respectively. This proves that nonlinearity comprising of magnetic field and quantum conditions together helps in enhancing self-focusing of the beam as compared with the case when quantum parameters or magnetic field is taken alone as obvious from Fig. 2.

## Numerical results and discussion

The second-order nonlinear differential equation (20) is solved numerically by the fourth-order Runge–Kutta method to study the behavior of the beam-width parameter "$f$" with the dimensionless distance of propagation ξ. The boundary conditions applied for numerical solutions of Eq. (20) are $f = 1$, $f' = 0$ at $\xi = 0$. The other parameters of laser and plasma are as follows: $\omega_0 = 1.778\times10^{20}$ rad/s, $r_0 = 0.003$ cm, $\lambda = 0.0106$ nm, $n_0 = 3.14\times10^{18}$ cm$^{-3}$, $\omega_c/\omega_0 = 0.1-0.3$, and plasma electron temperature $T_e$ are taken as 50, 75, 100, and 125 keV. The right-hand side of Eq. (20) is comprised of two terms which are responsible for convergence and divergence of the beam. The beam undergoes self-focusing when the second term dominates over the first term, while diffraction of the beam takes place when the first term dominates over the second term.

Figure 1a shows the plot for the nonlinear plasma dielectric function Φ against normalized laser intensity $A^2/A_{oo}^2$ at different values of plasma electron temperature $T_e = 50$, 75, 100, and 125 keV with the fixed value of magnetic field $\omega_c/\omega_0 = 0.3$.

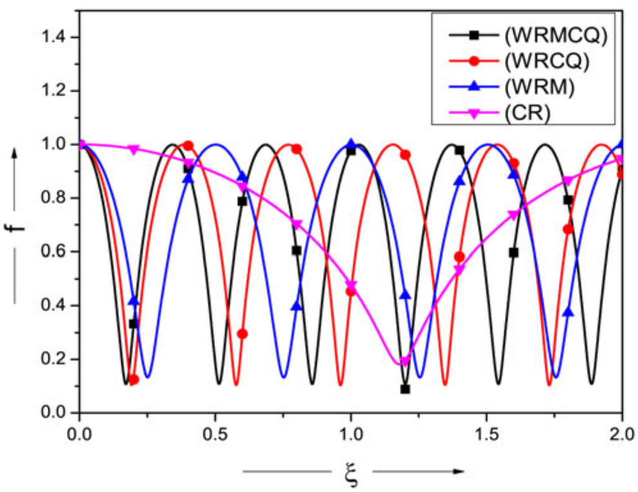


**Fig. 2.** Variation of the beam-width parameter "*f*" with the normalized propagation distance "ξ" for WRMCQ, WRCQ, WRM, and CR cases of references for the fixed value of plasma electron temperature $T_e = 50$ keV. The other parameters are same as mentioned in the caption of Fig. 1a.

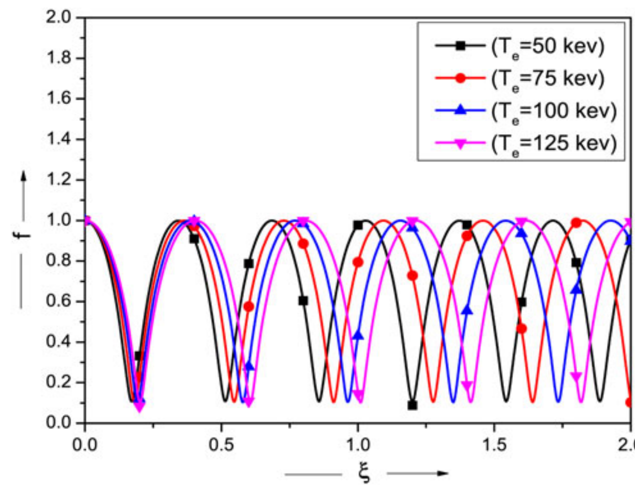


**Fig. 3.** Variation of the beam-width parameter "*f*" with the normalized propagation distance "ξ" at different values of plasma electron temperature $T_e = 50$, 75, 100, and 125 keV, the other parameters are same as mentioned in the caption of Fig. 1a.

Figure 2 shows the plot between the dimensionless beam-width parameter "*f*" and the dimensionless distance of propagation "ξ" for different nonlinearities, namely the beam propagation in plasma with (1) magnetic field (WRMCQ), (2) without magnetic field (WRCQ), (3) when quantum effects are neglected, δ = 0 (WRM), and the last curve is for classical relativistic case (CR). The values of magnetic field and electron temperature are $\omega_c/\omega_0 = 0.3$ and $T_e = 50$ keV, respectively. From the figure, it is clear that self-focusing is maximum for the WRMCQ case in which both magnetic field and quantum effects are taken as compared to their individual effects i.e. WRCQ and WRM plasma cases, respectively. The beam is least focused for the CR case of reference. Hence, we can conclude that plasma electron temperature ($T_e = 50$ keV) for which quantum effects are dominant assists the magnetic field and the pinching effect of quantum plasma further helps in increasing the self-focusing of the beam.

Figure 3 shows the plot between "*f*" and "ξ" at different values of plasma electron temperature, namely $T_e = 50$, 75, 100, and 125 keV for WRMCQ plasma. From the curve, it is clear that maximum self-focusing is obtained at the lowest electron temperature value, that is, at $T_e = 50$ keV. This is because at $T_e = 50$ keV, de-Broglie wavelength is found to be $\lambda_B = 1.06 \times 10^{-6}$ and $n_e\lambda_B^3 = 3.74 > 1$. Thus quantum effects are dominant at $T_e =$ 50 keV. Further, with the increase in $T_e$ values i.e. at $T_e = 75$, 100, and 125 keV, weaker self-focusing is observed. This is because at $T_e = 125$ keV, $\lambda_B = 6.71 \times 10^{-7}$, and $n_e\lambda_B^3 = 0.94 < 1$, quantum effects start diminishing with the rise in plasma electron temperature. Our results are in good agreement with Bokaei *et al.* (2013).

Figure 4 shows the variations of "*f*" versus "ξ" at different values of $\omega_c/\omega_0 = 0$, 0.1, 0.2, and 0.3 for the fixed electron temperature $T_e = 50$ keV. From the plot, we observe that with the increase in cyclotron frequency, the spot size of the beam decreases, and hence self-focusing of the beam increases. The reason is quite vivid that cyclotron frequency provided by the magnetic field adds to the natural oscillating frequency of the electrons and results in maximum self-focusing of the beam. This further increases the normalized laser intensity. So we have plotted the normalized laser intensity with beam radius in Fig. 5d at different values of $\omega_c/\omega_0 = 0$, 0.1, 0.2, and 0.3.

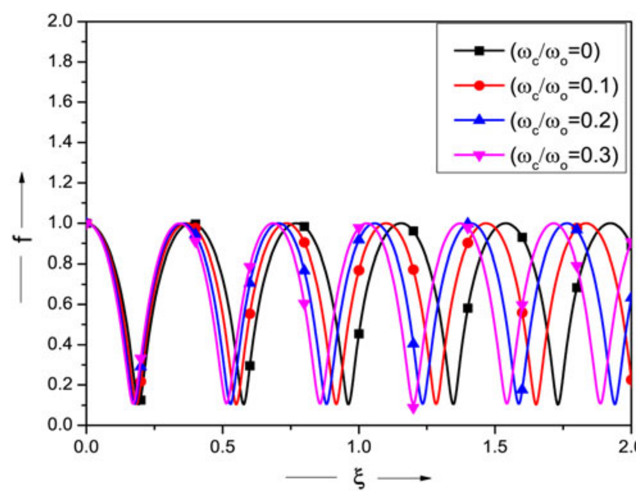


**Fig. 4.** Variation of the beam-width parameter "*f*" with the normalized propagation distance "ξ" at different values of $\omega_c/\omega_0 = 0$, 0.1, 0.2, and 0.3. The other parameters are same as mentioned in the caption of Fig. 1a.

Figure 5a is plotted for normalized intensity against normalized beam radius at $\omega_c/\omega_0 = 0.1$ for different values of plasma electron temperature $T_e = 50$, 75, 100, and 125 keV. In the similar case, Fig. 5b is plotted at the fixed value of $\omega_c/\omega_0 = 0.2$, and Fig. 5c is plotted at $\omega_c/\omega_0 = 0.3$, respectively. From these plots, it is observed that the beam intensity achieves maximum at $T_e =$ 50 keV and decreases in the order of increasing electron temperature values i.e. $T_e = 75$, 100, and 125 keV. Further, we have observed that the normalized intensity increases with the increase in cyclotron frequency. The normalized intensity achieved is about tenfolds in case of $T_e = 50$ keV as compared with $T_e =$ 125 keV (Fig. 5c). Figure 5d is sketched between normalized beam intensity and normalized beam radius at different values of magnetic field at $T_e = 50$ keV. The increase in intensity is about twelverfolds in case of $\omega_c/\omega_0 = 0.3$ as compared with $\omega_c/\omega_0 = 0.0$ (when no magnetic field is applied) at the fixed value of plasma electron temperature $T_e = 50$ keV. Thus, we can conclude that studying the plasma electron temperature along with

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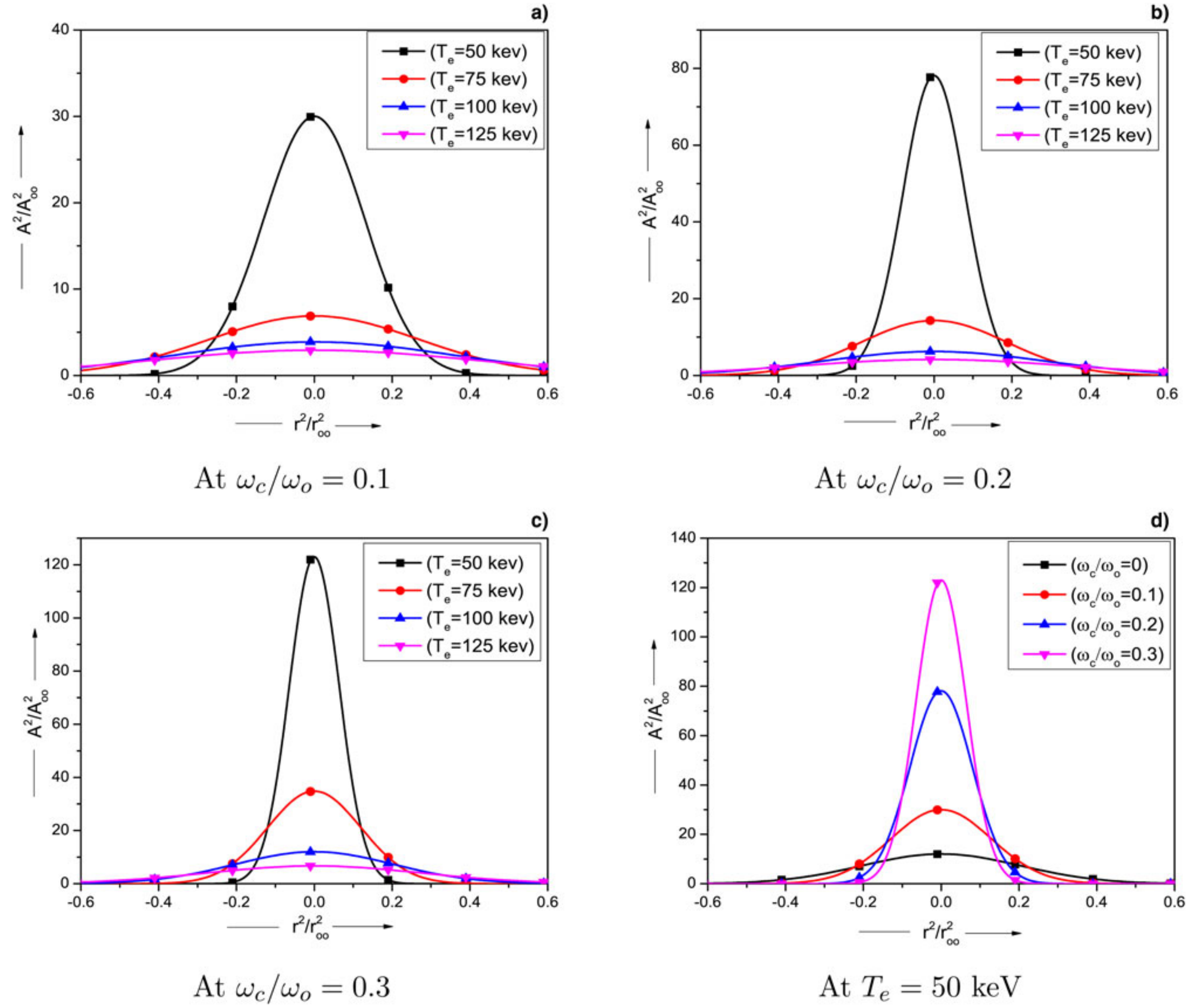


**Fig. 5.** Variation of the normalized beam intensity ($A^2/A^2_{oo}$) against normalized beam radius ($r^2/r^2_{oo}$) at different plasma electron temperature $T_e = 50$, 75, 100, and 125 keV (a) for $\omega_c/\omega_0 = 0.1$; (b) for $\omega_c/\omega_0 = 0.2$; (c) for $\omega_c/\omega_0 = 0.3$; and (d) at different values of magnetic field $\omega_c/\omega_0 = 0$, 0.1, 0.2, and 0.3 at $T_e = 50$ keV. The other parameters are same as mentioned in the caption of Fig. 1a.

magnetic field significantly assists in improving the beam propagation characteristics, as well as normalized intensity of the beam.

## Conclusions

(1) In the present investigation, we have studied the effect of electron plasma temperature and its vital role in improving the self-focusing in WRMCQ plasma for different plasma electron temperatures. For $T_e = 50$ keV, $\lambda_B = 1.06 \times 10^{-6}$ and $n_e\lambda_B^3 = 3.74 > 1$, the normalized intensity increases to many folds where quantum effects are dominant.

(2) The normalized intensity gains a boost of twelvefold in intensity at $\omega_c/\omega_0 = 0.3$ as compared tothe case when $\omega_c/\omega_0 = 0.0$ at a temperature $T_e = 50$ keV. Thus, we conclude that magnetic field assists quantum effects in improving the self-focusing of Gaussian laser beam.

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## References

**Aggarwal M, Goyal V, Kumar H, Richa K and Gill TS** (2017*a*) Weakly relativistic self-focusing of Gaussian laser beam in magnetized cold quantum plasma. *Laser and Particle Beams* **35**, 699–705.

**Aggarwal M, Kumar H, Richa K and Gill TS** (2017*b*) Self-focusing of Gaussian laser beam in weakly relativistic and ponderomotive cold quantum plasma. *Physics of Plasmas* **24**, 013108.

**Akhmanov SA, Sukhorukov AP and Khokhlov RV** (1968) Self-focusing and diffraction of light in a nonlinear medium. *Soviet Physics Uspekhi* **10**, 609–636.

**Ang LK and Zhang P** (2007) Ultrashort-pulse Child–Langmuir law in the quantum and relativistic regimes. *Physical Review Letters* **98**, 164802.

**Ang LK, Koh WS, Lau YY and Kwan TJT** (2006) Space-charge-limited flows in the quantum regime. *Physics of Plasmas* **13**, 056701.

**Barens W, Dereux A and Ebbensen T** (2003) Surface plasmon subwavelength optics. *Nature* **424**, 824–830.

**Benvenuto OG and De Vito MA** (2005) The formation of helium white dwarfs in close binary systems – II. *Monthly Notices of the Royal Astronomical Society* **362**, 891.

**Betti R and Hurricane OA** (2016) Inertial-confinement fusion with lasers. *Nature Physics* **12**, 435.

**Bokaei B, Niknam AR and Jafari Milani MR** (2013) Turning point temperature and competition between relativistic and ponderomotive effects in self-focusing of laser beam in plasma. *Physics of Plasmas* **20**, 103107.

**Chabrier G, Douchin F and Potekhin AY** (2002) Dense astrophysical plasmas. *Journal of Physics: Condensed Matter* **14**, 9133.

**Darian MM, Abari ME and Sedaghat M** (2016) The effect of external magnetic field on the density distributions and electromagnetic fields in the interaction of high-intensity short laser pulse with collisionless underdense plasma. *Journal of Theoretical and Applied Physics* **10**, 33–39.

**Gill TS, Kaur R and Mahajan R** (2010) Propagation of high power electromagnetic beam in relativistic magnetoplasma: higher order paraxial ray theory. *Physics of Plasmas* **17**, 093101.

**Gondarenko NA** (2005) Generation and evolution of density irregularities due to self-focusing in ionospheric modifications. *Journal of Geophysical Research* **110**, A09304.

**Gonsalves AJ, Nakamura K, Lin C, Panasenko D, Shiraishi S, Sokollik T, Benedetti C, Schroeder CB, Geddes CGR, van Tilborg J, Osterhoff J, Esarey E, Toth C and Leemans WP** (2011) Tunable laser plasma accelerator based on longitudinal density tailoring. *Nature Physics* **7**, 862–866.

**Gupta DN, Islam MR, Jang DG, Suk H and Jaroszynsk DA** (2013) Self-focusing of a high-intensity laser in a collisional plasma under weak relativistic-ponderomotive nonlinearity. *Physics of Plasmas* **20**, 123103.

**Harding AK and Lai D** (2006) Physics of strongly magnetized neutron stars. *Reports on Progress in Physics. Physical Society (Great Britain)* **69**, 2631.

**Kant N, Gupta DN and Suk H** (2011) Generation of second-harmonic radiations of a self-focusing laser from a plasma with density-transition. *Physics Letters A* **375**, 3134–3137.

**Killian TC** (2006) Experiments in Botany. *Nature (London)* **441**, 298.

**Kumar H and Aggarwal M** (2018) Self-focusing of elliptic-Gaussian laser beam in relativistic ponderomotive plasma using a ramp density profile. *Journal of the Optical Society of America B* **35**, 1635–1641.

**Kumar H, Aggarwal M, Richa K, Gill TS** (2016) Combined effect of relativistic and ponderomotive nonlinearity on self-focusing of Gaussian laser beam in a cold quantum plasma. *Laser and Particle Beams* **12**, 426–432.

**Landau LD and Lifshitz EM** (1980) *Statistical Physics*. Oxford: Butterworth-Heinemann, pp. 1908–1968.

**Leemans WP, Nagler B, Gonsalves AJ, Tóth Cs., Nakamura K, Geddes CGR, Esarey E, Schroeder CB and Hooker SM** (2006) GeV electron beams from a centimetre-scale accelerator. *Nature Physics* **2**, 696–699.

**Mahajan R, Gill TS, Kaur R and Aggarwal M** (2018) Stability and dynamics of a Cosh-Gaussian laser beam in relativistic thermal quantum plasma. *Laser and Particle Beams* **36**, 341–352.

**Malik HK and Aria AK** (2010) Microwave and plasma interaction in a rectangular waveguide: effect of ponderomotive force. *Journal of Applied Physics* **108**, 013109.

**Markowich PA, Ringhofer CA and Schmeiser C** (1990) *Semiconductor Equations*. New York: Springer-Verlag.

**Milani MRJ, Niknam AR and Bokaei B** (2014) Temperature effect on self-focusing and defocusing of Gaussian laser beam propagation through plasma in weakly relativistic regime. *IEEE Transactions on Plasma Science* **42**, 742–747.

**Niknam AR, Hashemzadeh M and Shokri B** (2009) Weakly relativistic and ponderomotive effects on the density steepening in the interaction of an intense laser pulse with an underdense plasma. *Physics of Plasmas* **16**, 033105.

**Niknam AR, Barzegar S and Hashemzadeh M** (2013) Self-focusing and stimulated Brillouin back-scattering of a long intense laser pulse in a finite temperature relativistic plasma. *Physics of Plasmas* **20**, 122117.

**Opher M, Silva LO, Dauger DE, Decky VK and Dawson JM** (2001) Nuclear reaction rates and energy in stellar plasmas: the effect of highly damped modes. *Physics of Plasmas* **8**, 2454–2460.

**Ouahid L, Dalil-Essakali L and Belafhal A** (2018) Effect of light absorption and temperature on self-focusing of finite Airy–Gaussian beams in a plasma with relativistic and ponderomotive regime. *Optical and Quantum Electronics* **50**, 216.

**Pandey B and Tripathi VK** (2009) Anomalous transmission of an intense short-pulse laser through a magnetized overdense plasma. *Physica Scripta* **79**, 025101.

**Patil SD, Takale MV, Navare ST, Dongare MB and Fulari VJ** (2013) Self-focusing of Gaussian laser beam in relativistic cold quantum plasma. *Optik* **124**, 180–183.

**Patil SD, Chikode PP and Takale MV** (2018) Turning point temperature of self-focusing at laser–plasma interaction with weak relativistic-ponderomotive nonlinearity: effect of light absorption. *Journal of Optics (2010)* **47**, 174–179.

**Ping XX and Lin Y** (2012) Effect of higher order axial electron temperature on self-focusing of electromagnetic pulsed beam in collisional palsma. *Communications in Theoretical Physics* **57**, 873–878.

**Roth M, Cowan TE, Key MH, Hatchett SP, Brown C, Fountain W, Johnson J, Pennington DM, Snavely RA, Wilks SC, Yasuike K, Ruhl H, Pegoraro F, Bulanov SV, Campbell EM, Perry MD and Powell H** (2001) Fast ignition by intense laser-accelerated proton beams. *Physical Review Letters* **86**, 436.

**Sharma A, Koueakis I and Sodha MS** (2008) Propagation regimes for an electromagnetic beam in magnetized plasma. *Physics of Plasmas* **15**, 103103.

**Sodha MS and Sharma A** (2008) Self-focusing of electromagnetic beams in the ionosphere considering Earth's magnetic field. *Journal of Plasma Physics* **74**, 473.

**Sodha MS, Ghatak AK and Tripathi VK** (1976) Self-focusing of laser beams in plasmas and semiconductors. *Progress in Optics* **13**, 169–265.

**Tabak M, Hammer J, Glinsky ME, Kruer L, Wilks SC, Woodworth J, Campbell EM, Perry MD and Mason RD** (1994) Ignition and high gain with ultrapowerful lasers. *Physics of Plasmas* **1**, 626.

**Varaki MA and Jafari S** (2017) Self-focusing and de-focusing of intense left and right-hand polarized laser pulse in hot magnetized plasma: laser output power and laser spot-size. *Optik* **142**, 360–369.

**Walia K, Tripathi D and Tyagi Y** (2017) Investigation of weakly relativistic ponderomotive effects on self-focusing during interaction of high power elliptical laser beam with plasma. *Communications in Theoretical Physics* **68**, 245–249.

**Wang Y and Zhou Z** (2011) Propagation characters of Gaussian laser beams in collisionless plasma: effect of plasma temperature. *Physics of Plasmas* **18**, 043101.

**Zare S, Yazdani E, Rezaee S, Anvari A and Sadighi-Bonabi R** (2015) Relativistic self-focusing of intense laser beam in thermal collisionless quantum plasma with ramped density profile. *Physical Review Special Topics – Accelerators and Beams* **18**, 041301.

**Zhang P and Thomas AGR** (2015) Enhancement of high order harmonic generation in the intense laser interactions with solid density plasma by multiple reflections and harmonic amplification. *Applied Physics Letters* **106**, 131102.