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Effect of an external magnetic field on the self-focusing of a cosh-Gaussian laser beam in plasma under the relativistic-ponderomotive effect

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Abstract

This work presents an analytical and numerical study of the relativistic-ponderomotive effect on self-focusing of an intense cosh-Gaussian laser beam in a collisionless magnetized plasma by considering an external magnetic field in the direction of propagation of the laser beam. The nonlinear differential equation for the beam width parameter/intensity of a cosh-Gaussian laser beam in a magnetized plasma is obtained by Wentzel–Kramers–Brillouin (WKB) and paraxial-ray approximations. The self-focusing of the cosh-Gaussian beam at different values of the magnetic field parameter is investigated. The results have also been compared to relativistic nonlinearity. The results show that the self-focusing effect of cosh- Gaussian beam in magnetized plasma becomes stronger, when relativistic and ponderomotive nonlinearities acts together. In addition, the self-trapping of cosh-Gaussian beam in magnetized plasma has also been studied. Numerical results are presented for the well-established laser and plasma parameters.

1 Introduction

The nonlinear interaction of an ultra-high-intensity laser pulse with plasma is of wide importance in many fields, including inertial confinement fusion [1,2], particle accelerators [3], new radiation sources [4], high harmonic generation [5], THz radiation [6] and X-ray lasers [7]. Efficient coupling of laser energy with plasma is highly essential for the successful implementation of these applications. The laser beam must be propagated over extended distances at high intensities in the plasma without loss of energy. At such a long distance in the plasma, the laser beam encounters various instabilities such as self-focusing, filamentation, stimulated Raman scattering (SRS), stimulated Brillouin scattering (SBS), two plasmon decay (TPD) etc., which impede the laser plasma coupling [8]. Self-focusing is the most important nonlinear process in laser plasma interaction because all other processes are strongly affected by self-focusing.

The propagation of a laser beam in a plasma is described by self-focusing, which is caused by a change in the refractive index of the plasma due to the high intensity of laser beam. The nonlinearity of the medium is mainly attributed to the self-focusing of the laser beam which is generated upon its interaction with the laser field. Self-focusing of laser beams in plasma at high intensities is characterized by relativistic and ponderomotive non-linearity [9,10]. These nonlinearities modify the plasma refractive index by various mechanisms, leading to self-focusing of the laser beam. Relativistic nonlinearity arises due to the relativistic motion of electrons, which establishes the relativistic self-focusing. On the other hand, ponderomotive nonlinearity is established due to the ponderomotive force associated with an intense laser beam, which is directed along the gradient of the laser intensity. The ponderomotive force pushes electrons out of the high-intensity region and lowers the electron density. The refractive index of plasma increases in the high intensity region, leading to ponderomotive self-focusing of the laser beam in the plasma. The combined effect of these nonlinearities contributes significantly to the stronger and earlier focusing of the laser beam in the plasma.

Self-focusing of laser beams in unmagnetized plasma has been investigated to a great extent [11-18]. When an intense laser beam interacts with a plasma, strong magnetic fields are generated [19, 20] that affect the propagation of the laser beam in the plasma because the canonical momentum is not conserved for the magnetic plasma to interact with the intense radiation [21]. This is particularly relevant for the fast-ignition scheme of inertial confinement fusion, where quasi-static self-generated magnetic fields can exist in a low-density corona region close to the

critical surface of the ignition pulse [22]. The laser-induced velocity of plasma electrons increases significantly in the presence of a magnetic field, which further modifies the nonlinear dielectric constant of the plasma. As a result, the magnetic field strengthens the self-focusing of the laser beam in the plasma [23]. The self-focusing of an intense laser beam into a magnetized plasma has been investigated in various studies with relativistic/ponderomotive nonlinearity, where various profiles of laser beams such as Gaussian [24], super Gaussian [25,26], hollow Gaussian [27], q-Gaussian [28], Hermite-Gaussian [30] etc. have been used. These studies conclude that the self-focusing of the laser beam is increased in the presence of a magnetic field.

In the present paper, the effect of an external magnetic field on the self-focusing of cosh-Gaussian laser beam in a collisionless plasma under paraxial-ray approximation is explored. This study is performed in the presence of a combined effect of relativistic and ponderomotive nonlinearities and the results are compared with only relativistic nonlinearity. The cosh-Gaussian profile of a laser beam (decentered Gaussian beam) is chosen because it has more power than a Gaussian laser beam and its intensity is greater near the axis of propagation [31,32]. Various studies have explored the effect of the decentered parameter, incident laser intensity, and plasma density on the self-focusing of a cosh-Gaussian laser beam in the plasma [32-37]. But the self-focusing of cosh-Gaussian laser beam in plasma have not been studied to a significant extent in the presence of an external magnetic field, when the combined effect of relativistic and ponderomotive nonlinearities is taken into the account. With this in mind, we have specifically analyzed the effect of the magnetic field on the relativistic ponderomotive self-focusing of an intense cosh-Gaussian laser beam in plasma. The effect of the magnetic field on the self-trapping of the cosh-Gaussian laser beam is also investigated.

2 Analytical model

Consider the propagation of a linearly polarized cosh-Gaussian laser beam of frequency (ω_0) and wave vector (k_0) in the direction of the static magnetic field (\vec{B}_0) along the z -direction in a collisionless magnetized plasma. The electric field vector of the laser beam can be written as:

$$\vec{E}_L = \hat{x}A_0(r, z)\exp[-i(\omega_0 t - k_0 z)] \quad (1)$$

where $k_0 = \frac{\omega_0}{c}(\epsilon_0)^{1/2}$ is the propagation constant of the beam and ϵ_0 is the dielectric constant of plasma. The initial amplitude (A_0) of the cosh-Gaussian laser beam is given by [30, 38]

$$(A_0)_{z=0} = \frac{E_0}{2f} \exp\left(\frac{b^2}{2}\right) \left[\exp\left\{-\left(\frac{r}{r_0 f} + \frac{b}{2}\right)^2\right\} + \exp\left\{-\left(\frac{r}{r_0 f} - \frac{b}{2}\right)^2\right\} \right] \quad (2)$$

where E_0 is the amplitude of the CGLB, b is the decentered parameter of the beam, r_0 is the initial width of the beam, and f is the dimensionless beam width parameter of the beam.

The dielectric constant of the plasma is given by

$$\epsilon_0 = \left[1 - \frac{\omega_{p0}^2}{\omega_0^2 \left(1 - \frac{\omega_{ce}}{\omega_0}\right)} \right]^{1/2} \quad (3)$$

where $\omega_{p0} \left[= \left(\frac{4\pi m_0 e^2}{m_0}\right)^{1/2} \right]$ the plasma frequency, and $\omega_{ce} \left[= \frac{eB_0}{m_0 c} \right]$ is the electron cyclotron

frequency. Cyclotron motion in charged particles of plasma is induced by static magnetic fields.

The oscillatory velocity of electrons imparts by the laser beam is

$$\vec{v}_0 = \frac{ie}{m_0 \omega_0 \gamma \left(1 - \frac{\omega_{ce}}{\gamma \omega_0}\right)} \vec{E}_L \quad (4)$$

The relativistic factor $\gamma \left[= \left(1 - \frac{v_0^2}{c^2}\right)^{1/2} \right]$ can be defined as

$$\gamma = \left[1 + \frac{e^2 |A_0|^2}{m_0^2 c^2 \omega_0^2 \left(1 - \frac{\omega_{ce}}{\omega_0}\right)^2} \right]^{1/2} = \left[1 + \frac{a^2}{\left(1 - \frac{\omega_{ce}}{\omega_0}\right)^2} \right]^{1/2} \quad (5)$$

where $a^2 = \frac{e^2 |A_0|^2}{m_0^2 \omega_0^2 c^2}$.

Further, the relativistic-ponderomotive (RP) force produced due to laser beam is given by [14,16]

$$F_{RP} = -m_0 c^2 \nabla(\gamma - 1) \quad (6)$$

The electron plasma density is modified by (RP) force. The modified density is given by [16]

$$n = n_0 + n_2 = n_0 + \frac{c^2 n_0}{\omega_{p0}^2} \left(\nabla^2 \gamma - \frac{(\nabla \gamma)^2}{\gamma} \right) \quad (7)$$

where n_2 is the second order correction term in the electron density equation, which has been solved using electron continuity equation and current density equation. Eq. (7) can be written as

$$\frac{n}{n_0} = 1 + \frac{c^2}{\omega_{p0}^2} \left(\nabla^2 \gamma - \frac{(\nabla \gamma)^2}{\gamma} \right) \quad (8)$$

The effective dielectric constant of plasma in the presence of relativistic-ponderomotive nonlinearity can be written as

$$\varepsilon = \varepsilon_0 + \phi_N (\vec{E}_L \cdot \vec{E}_L^*) \quad (9)$$

where

$$\phi_N (\vec{E}_L \cdot \vec{E}_L^*) = 1 - \frac{\omega_{p0}^2}{\omega_0^2} \left(\frac{1 - \frac{\omega_{ce}}{2\omega_0}}{\left(1 - \frac{\omega_{ce}}{\omega_0}\right)^2} \left(1 - \frac{n}{n_0 \gamma}\right) \right)$$

is the nonlinear part of the dielectric constant.

To investigate the self-focusing of cosh-Gaussian laser beam in the magnetized plasma, expanding the effective dielectric constant in the paraxial regime around $r = 0$ by using Taylor expansion, one can write

$$\varepsilon = \varepsilon_1 + \phi_1 r^2 \quad (10)$$

where

$$\varepsilon_1 = \Omega^2 - \frac{\Omega^2}{\gamma} - \Omega^2 \frac{c^2 a (4b^2 - 16)}{4\omega_{p0}^2 \gamma^2 r_0^2 f^4} \left(1 - \frac{\omega_c}{\omega_0}\right)^{-2}$$

and

$$\phi_N = -\Omega^2 \left(1 - \frac{\omega_c}{\omega_0}\right)^{-2} \left[\frac{a}{\gamma^3 f^4 r_0^2} + \frac{ac^2}{\omega_{p0}^2 f^2} \left[\frac{(16 - 4b^2)}{\gamma^2 f^4 r_0^4} + \frac{2a}{\gamma^4 f^6 r_0^4} \left((b^2 - 4) \left(1 - \frac{\omega_c}{\omega_0}\right)^{-2} - 4 \right) \right] \right]$$

Here $\Omega = \frac{\omega_{p0}^2}{\omega_0(\omega_0 - \omega_c)}$, and $a = \alpha A_0^2 \left(\alpha = \frac{e^2}{m_0^2 \omega_0^2 c^2} \right)$ is the intensity parameter.

Using Maxwell's equations, the wave equation for the electric field vector (\vec{E}_L) of the beam in the plasma can be written as

$$\nabla^2 \vec{E}_L + \frac{\omega_0^2}{c^2} \varepsilon(r, z) \vec{E}_L = 0 \quad (11)$$

For linearly polarized cosh-Gaussian laser beam, the term $\nabla(\nabla \cdot \vec{E}_L)$ can be neglected in Eq. (11)

as long as $\left(\frac{c^2}{\omega_0^2}\right) \left(\frac{1}{\varepsilon}\right) \nabla^2 \ln \varepsilon \ll 1$.

The electric field variation of the beam is given by [11]

$$\vec{E}_L = A(r, z) \exp[i(\omega_0 t - k_0 z)] \quad (12)$$

where $A(r, z)$ is the complex amplitude of the electric field, which can be expressed as

$$A(r, z) = A_0 \exp[-ik(z)S(r, z)] \quad (13)$$

where A_0 and S are real functions of r and z , $S(r, z)$ is the eikonal of the beam, which shows converging/diverging characteristic of the beam in plasma.

Substituting Eqs. (11) and (12) into Eq. (10), and equating the real and imaginary parts, we obtain the following equations

$$2\left(\frac{\partial S}{\partial z}\right) + \left(\frac{\partial S}{\partial r}\right)^2 = \frac{1}{k^2 A_0} \left(\frac{\partial^2 A_0}{\partial r^2} + \frac{1}{r} \frac{\partial A_0}{\partial r}\right) - \frac{\phi_N}{\varepsilon_0} r^2 \quad (14)$$

and

$$\frac{\partial A_0^2}{\partial z} + \frac{\partial S}{\partial r} \frac{\partial A_0^2}{\partial r} + A_0^2 \left(\frac{\partial^2 S}{\partial r^2} + \frac{1}{r} \frac{\partial S}{\partial r}\right) = 0 \quad (15)$$

The solution of Eqs. (14) and (15) can be written as [11, 13]

$$S = S_0(z) + \frac{r^2}{2} \frac{1}{f(z)} \frac{df(z)}{dz} \quad (16)$$

and

$$A_0^2 = \frac{E_0^2}{4f^2} \exp\left(\frac{b^2}{2}\right) \left[\exp\left\{-\left(\frac{r}{r_0 f} + \frac{b}{2}\right)^2\right\} + \exp\left\{-\left(\frac{r}{r_0 f} - \frac{b}{2}\right)^2\right\} \right]^2 \quad (17)$$

where $S_0(z)$ is the phase shift. Substituting Eqs. (16) and (17) in Eq. (15) and equating the coefficient of r^2 , we obtain the expression for the beam width parameter (f) as

$$\frac{d^2 f}{d\xi^2} = \frac{12-12b^2-b^4}{3f^3} - \Omega'^2 \left(1 - \frac{\omega_c}{\omega}\right)^{-2} \frac{\omega}{c^2} \left[\frac{ar_0^2}{\gamma_0^3 f^3} + \frac{ac^2}{\omega_p^2 f} \left[\frac{(16-4b^2)}{\gamma_0^2 f^4} + \frac{2a}{\gamma_0^4 f^6} \left\{ (b^2-4) \left(1 - \frac{\omega_c}{\omega}\right)^{-2} - 4 \right\} \right] \right] \quad (18)$$

When only relativistic nonlinearity is operative (i.e. $\frac{n}{n_0} = 1$), the expression for the beam

width parameter (f) is given by

$$\frac{d^2 f}{d\xi^2} = \frac{12-12b^2-b^4}{3f^3} - \Omega'^2 \left(1 - \frac{\omega_c}{\omega}\right)^{-2} \frac{\omega^2 r_0^2 a}{f^3 \gamma_0^3 c^2} \quad (19)$$

where $\xi (= z/kr_0^2)$ is the dimensionless distance of propagation. When the value of $(d^2 f/d\xi^2)_{\xi=0}$ is negative, the beam converges while when $(d^2 f/d\xi^2)_{\xi=0}$ is positive, the beam diverges. This is due to the fact that when the value of $(d^2 f/d\xi^2)_{\xi=0}$ is negative/positive, the width of the beam decreases/increases. At $(d^2 f/d\xi^2)_{\xi=0} = 0$, the beam-width parameter will remain constant through the propagation direction [39, 40]. This condition is known as the critical condition under which the beam propagates without convergence or divergence. This condition is also known as uniform waveguide mode of propagation or the self-trapped mode of laser beam. By putting $d^2 f/d\xi^2 = 0$ in Eq. (1), the relationship between the equilibrium beam radius $\rho_0 (= r_0 \omega_p/c)$ and the intensity parameter $a (= \alpha E_{00}^2)$ can be obtained, when relativistic and ponderomotive nonlinearities are taken into account. Therefore, the condition for self-trapping is

$$\rho_0^2 = \left(\frac{12-12b^2-b^4}{3a} \right) \frac{1}{a} \left(1 - \frac{\omega_c}{\omega}\right)^3 \gamma^3 - \left[(16-4b^2) \gamma + \frac{1}{\gamma} a \left((2b^2-8) \left(1 - \frac{\omega_c}{\omega}\right)^{-2} - 8 \right) \right] \quad (20)$$

When the initial conditions of a and ρ_0 satisfy Eq. (20), the induced self-focusing effect compensates the spatial diffraction. The laser beam propagates with constant beam width under this condition. However, the laser beam will converge or diverge if the initial value of ρ_0 is greater or less than the amount obtained by Eq. (20) for the defined laser intensity (a).

3 Numerical results and discussion

To study the effects of an external magnetic field on the self-focusing of a cosh-Gaussian laser beam in a plasma, we have performed numerical calculations of Eqs. (17) and (18) for the following set of laser and plasma parameters:

$\omega_0=1.778\times 10^{15}$ rad/s, $r_0=25\mu\text{m}$, $\omega_{p0}=5.34\times 10^{14}$ rad/s, $b=0.5$, the initial laser beam intensity (a) is in order of 1.21×10^{18} W/cm² corresponding to ($a=1$),

For the initial plane wave front of the beam, the initial conditions for f are $f=1$ and $df/dz=0$ at $z=0$. These parameters satisfy the condition for self-focusing of the cosh-Gaussian laser beam in the plasma with the magnetic field.

Equation (18) describes the converging/diverging behaviour of a cosh-Gaussian laser beam in a magnetized plasma, where the first term on the right-hand side shows the diffractive divergence and the second term represents the nonlinear refraction of the beam, which arises due to the combined effect of relativistic and ponderomotive nonlinearity. The relative magnitudes of the diffraction term and the nonlinear term determine the focusing/ defocusing behaviour of the beam in the plasma. The intensity profile of a cosh-Gaussian laser beam in plasma with relativistic and ponderomotive nonlinearities is given by Eq. (17), which shows that the beam intensity depends on the beam width parameter (f). Equations (17) and (18) have been solved numerically and the results are presented in the form of Figures (1-6).

Figures 1 and 2 represent the variation of the dimensionless beam width parameter (f) and the normalized intensity of the cosh-Gaussian laser beam, when only relativistic nonlinearity (RNL) and relativistic-ponderomotive nonlinearity (RPNL) are operative in the magnetized plasma and the paraxial approximation is taken into consideration. The focusing and intensity pattern of the beam varies from relativistic non-linearity to relativistic-ponderomotive non-linearity because the relativistic and ponderomotive nonlinearities in plasma depend on the total intensity of the beam. Electrons are expelled from the high-intensity region due to the ponderomotive force and the nonlinearity in the plasma comes from electron mass variation due to laser intensity. As the laser beam propagates through the plasma, the laser becomes self-focused due to the laser plasma coupling. It is clear from Fig. 1 that the extent of focusing of the cosh-Gaussian laser beam is stronger in the magnetized plasma when the combined effect of relativistic and ponderomotive nonlinearity is taken into the account. Furthermore, Fig. 2 shows that the laser beam intensity becomes higher due to the strong self-focusing of the cosh-Gaussian laser beam in the relativistic-ponderomotive regime. It is clear that the maximum intensity of the beam increases by a factor of about 9 when both nonlinearities are present.

Figures 3 and 4 present the variation of the beam-width parameter (f) of a cosh-Gaussian laser beam in a magnetized plasma with the normalized propagation distance (ξ) for different

values of normalized cyclotron frequency (ω_c), when the effect of relativistic - ponderomotive nonlinearities and only relativistic nonlinearity is taken into account. It is observed that the beam becomes self-focused in both the cases. The width of the beam decreases with an increase in ω_c . An increase in the value of ω_c leads to an increase in the self-focusing property of the beam. However, in both cases the beam becomes defocused at a higher value of ω_c ($= 1.2$). When $\omega_c > \omega$, the beam is defocused in the plasma. This is because the nonlinear term dominates over the diffraction term in Eqs. (1) and (2) at higher values of ω_c . It is also clear from the figures that the extent of self-focusing of the cosh-Gaussian laser beam increases when the relativistic nonlinearity act together with the ponderomotive nonlinearity.

The variation of the laser beam intensity with the normalized propagation distance corresponding to Figs. (3) and (4) for self-focusing region is shown in Figs. (5) and (6), when relativistic and ponderomotive nonlinearities and only relativistic nonlinearity are functional. Due to the strong self-focusing of the laser beam at higher values of ω_c in the plasma, the laser beam intensity increases in both cases. In the absence of a magnetic field ($\omega_c = 0$), the intensity is minimum. The static magnetic field increases the strength of the $\vec{v}_0 \times \vec{B}_0$ force and induce cyclotron motion in the charged particles (electrons) of a plasma, which further enhances the intensity of laser beam in the plasma. It is observed that the intensity becomes maximum in the relativistic-ponderomotive regime (by a factor of about 10) compared to the relativistic regime at $\omega_c = 0, 2\omega$ due to the inclusion of ponderomotive nonlinearity.

To better explain the underlying physics for the propagation of a cosh-Gaussian laser beam in a magnetized plasma, we solved equation (20) numerically and analyzed the dependence of ρ_0 as a function of a for different values of ω_c when relativistic and ponderomotive nonlinearities are taken into account. The results are shown in Figure 7 and 8, which show the variation of the dimensionless equilibrium beam radius (ρ_0) with initial intensity parameter (a) for different values of ω_c . It is seen that a monotonic fall of ρ_0 is found with a and b at $\omega_c = 0$. A similar change of ρ_0 with a is observed for higher values of ω_c . When the value of ω_c increases, initially a slow fall in ρ_0 is observed with a which becomes very slow with further increase in a . Eventually ρ_0 becomes almost independent of a and b . From Figure 7 and 8, it is seen that ρ_0 becomes smaller at the higher values of ω_c and its stabilization can be achieved at higher values of a and b with suitable value of ω_c .

4 Conclusions

In the present investigation, we have studied the self-focusing of a cosh-Gaussian laser beam in plasma in the presence of an external magnetic field, when the effect of relativistic and ponderomotive nonlinearity is taken into account. The coupled nonlinear differential equations for the beam-width parameter/intensity of the cosh-Gaussian laser beam are obtained through the parabolic equation approach under WKB and paraxial approximation. The results are compared with relativistic nonlinearity. It is observed that the self-focusing/intensity of the beam strengthens/increases in the relativistic-ponderomotive regime as compared to the relativistic regime for the same set of parameters. The self-focusing length and minimum beam width in the relativistic-ponderomotive case are significantly reduced compared to the relativistic case. The magnetic field (cyclotron frequency) significantly affects the self-focusing of the cosh-Gaussian laser beam in the plasma and plays important role in determining the nature of the beam's self-focusing/defocusing. The numerical results show that the self-focusing limit and beam intensity increase in both the relativistic-ponderomotive and relativistic regimes at higher values of the magnetic field. The self-focusing/intensity of the beam is stronger/increased in the relativistic-ponderomotive regime than in the relativistic regime due to the contribution of the ponderomotive effect. In addition, self-trapping of the beam has also been studied. The beam radius is smaller at higher values of ω_c which suggests that the beam radius becomes stable at higher values of a , b and ω_c . The results presented in this study may be useful in understanding the physics of laser plasma coupling in the presence of strong magnetic field.

Declarations

Conflict of interest: The authors declare no conflicts of interest.

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Data availability: Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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FIGURES

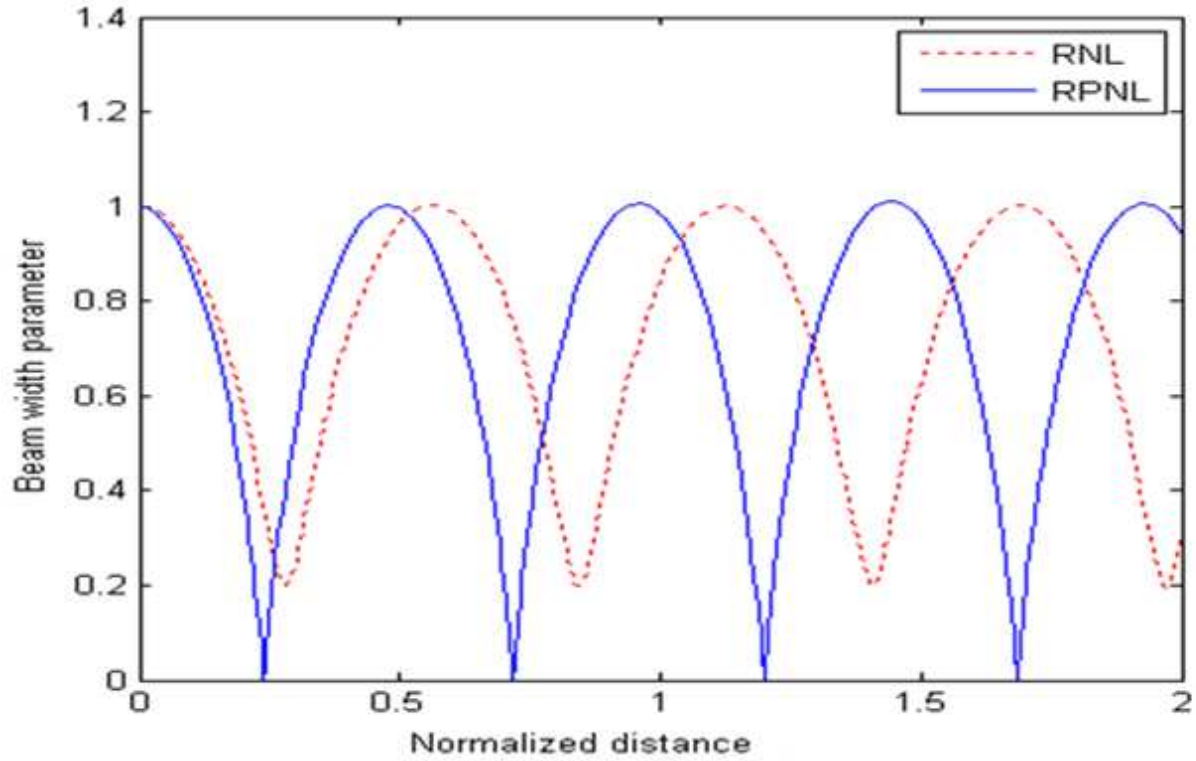


Figure 1. Comparison of the propagation characteristics of cosh-Gaussian laser beam in magnetized plasma when relativistic-ponderomotive nonlinearity (RPNL) and only relativistic nonlinearity (RNL) are functional. The typical parameters are $a = 1$, $b = 0.5$ and $\omega_c/\omega = 0.2$.

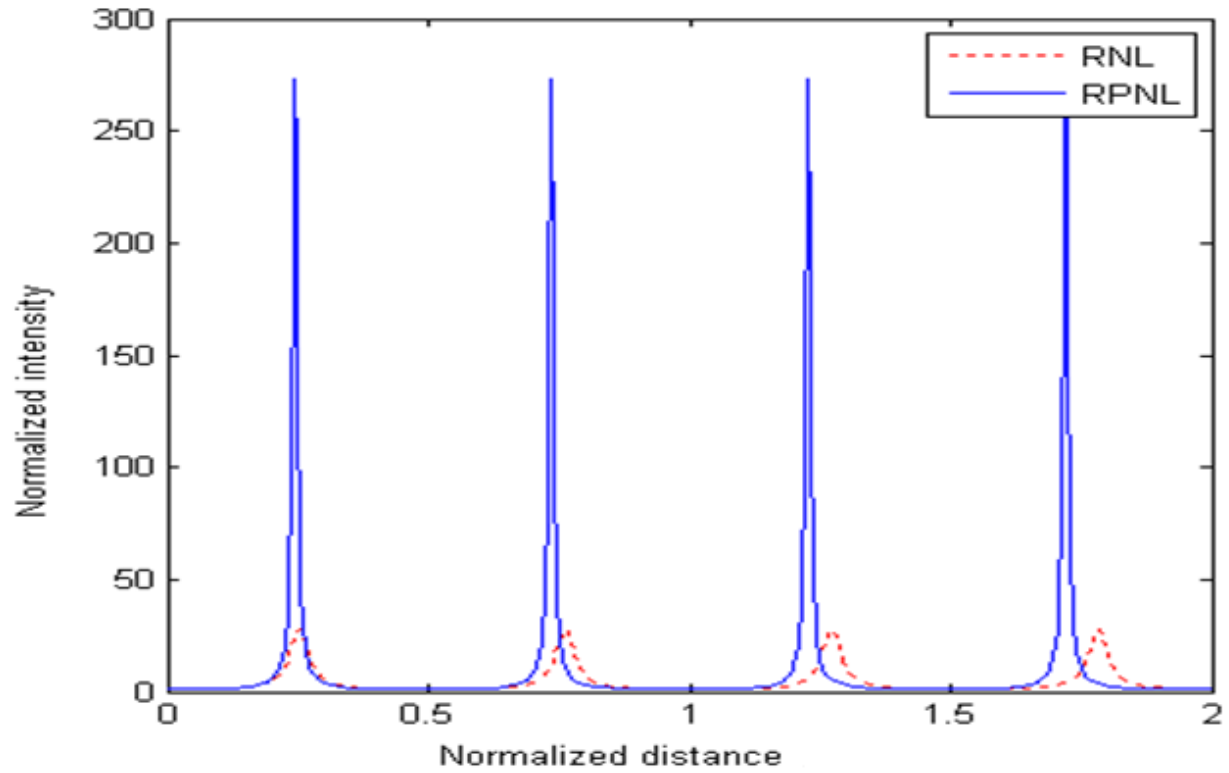


Figure 2. Normalized intensity of the cosh-Gaussian laser beam in a magnetized plasma for $a = 1$, $b = 0.5$ and $\omega_c/\omega = 0.2$, when relativistic-ponderomotive nonlinearity (RPNL) and only relativistic nonlinearity (RNL) are functional.

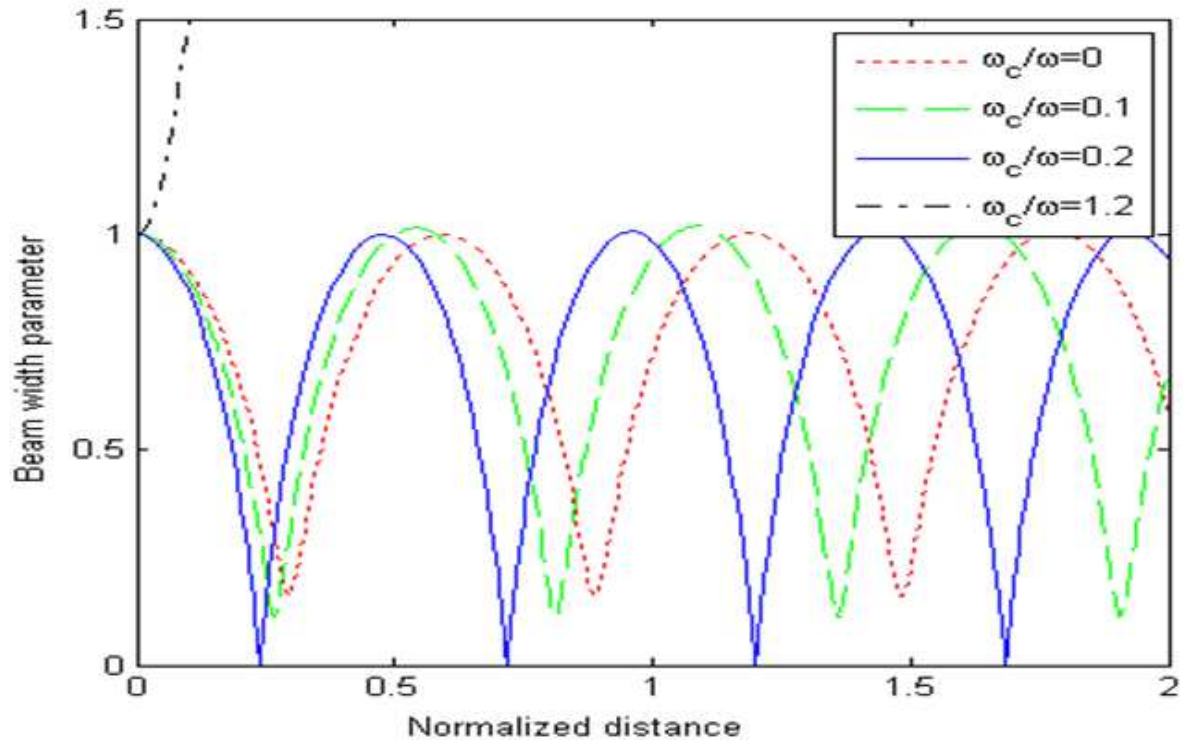


Figure 3. Variation of the beam width parameter (f) of a cosh-Gaussian laser beam for different values of cyclotron frequency (ω_c) with the normalized distance of propagation (ξ), with $a = 1$ and $b = 0.5$, when the relativistic-ponderomotive nonlinearity (RPNL) is operated.

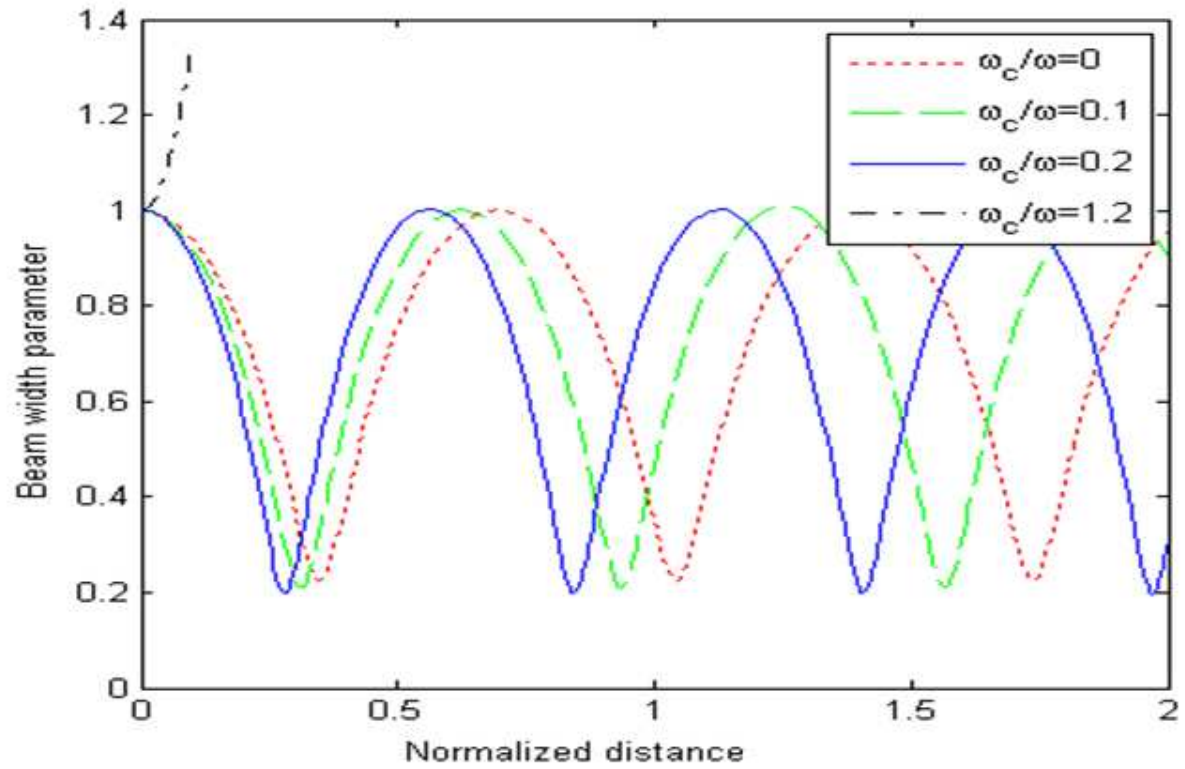


Figure 4. Variation of the beam width parameter (f) of the cosh-Gaussian laser beam for different values of cyclotron frequency (ω_c) with the normalized distance of propagation (ξ), with $a = 1$ and $b = 0.5$, when only relativistic nonlinearity (RNL) operates.

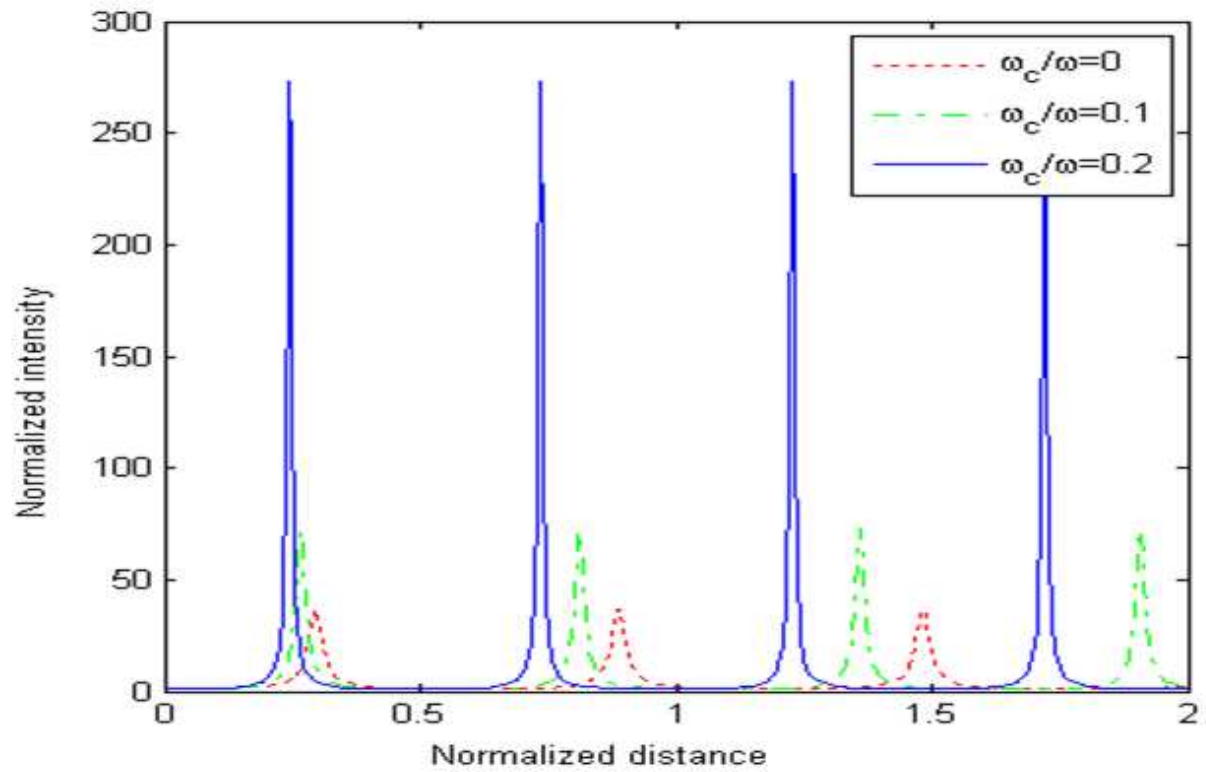


Figure 5. Normalized intensity of cosh-Gaussian laser beam in a magnetized plasma for different values of cyclotron frequency (ω_c) with normalized distance of propagation (ξ) at $a = 1$ and $b = 0.5$, when the relativistic-ponderomotive nonlinearity (RPNL) is operated.

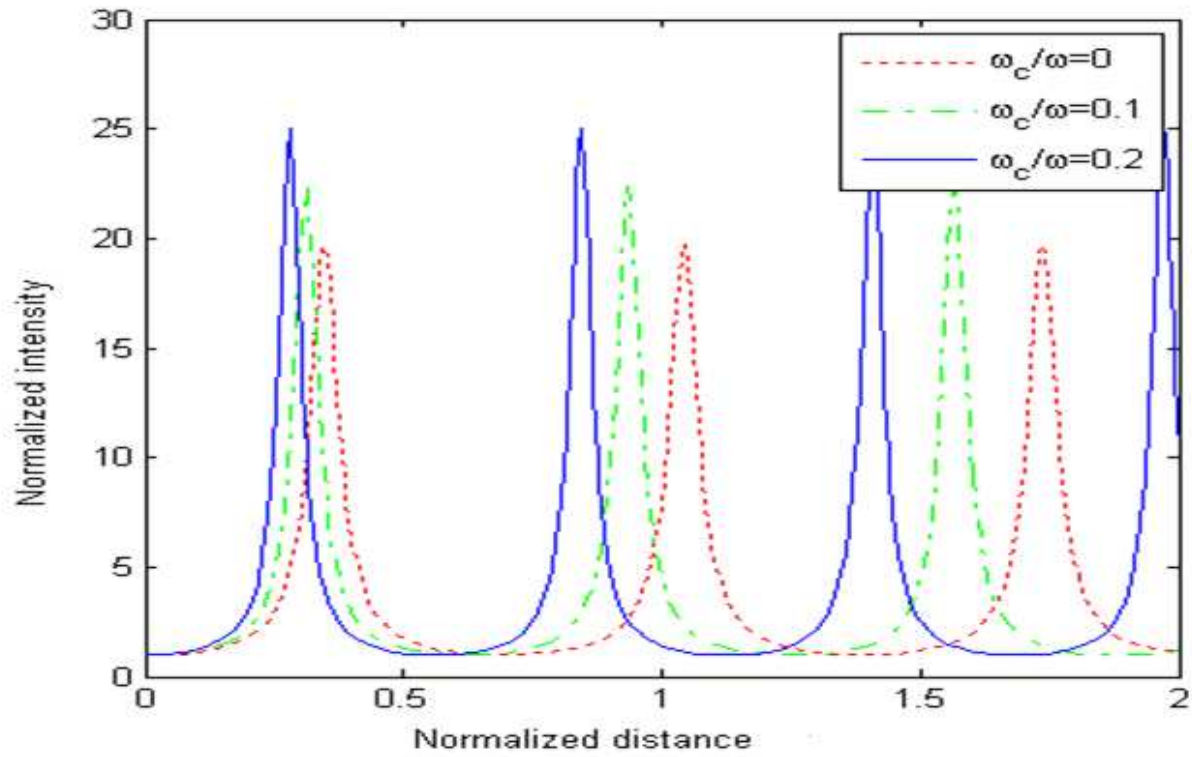


Figure 6. Normalized intensity of cosh-Gaussian laser beam in a magnetized plasma for different values of cyclotron frequency (ω_c) with normalized distance of propagation (ξ) at $a = 1$ and $b = 0.5$, when only relativistic nonlinearity is operated.

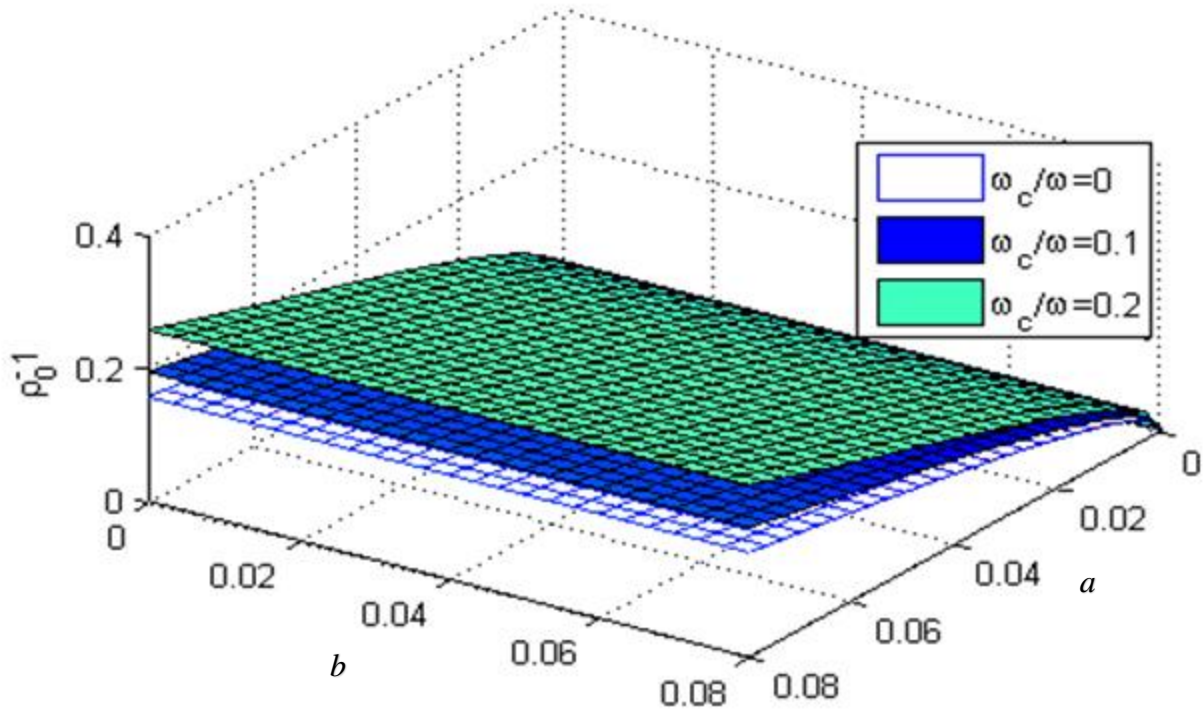


Figure 7. Dependence of ρ_0^{-1} with the intensity parameter (a) and decentered parameter (b) for different values of ω_c under self-trapped mode, when the relativistic-ponderomotive nonlinearity (RPNL) is operated.

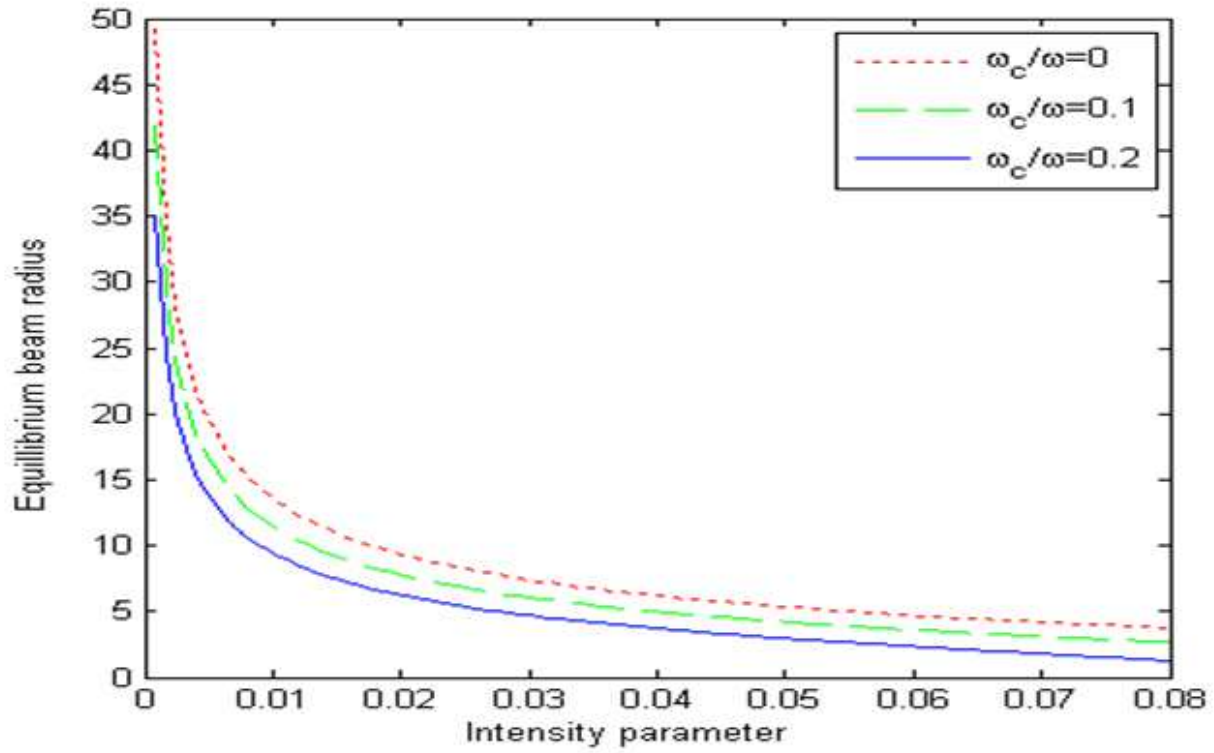


Figure 8. Dependence of the equilibrium beam radius (ρ_0) on the intensity parameter (a) for different values of ω_c under the self-trapped mode, when the relativistic-ponderomotive nonlinearity (RPNL) is operated.