Early and strong relativistic self-Focusing of cosh-Gaussian laser beam in cold quantum plasma

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\textbf{A B S T R A C T}

Relativistic self-focusing of cosh-Gaussian laser beam in the cold quantum plasma has been investigated theoretically. For a decentered parameter $b = 0.9$, we present a comparative analysis for self-focusing of cosh-Gaussian laser beam in relativistic cold quantum (RCQ) and classical relativistic (CR) case. It is observed that as the beam penetrates deeper inside the RCQ plasma, the self-focusing ability of the laser beam enhances and shifted towards lower value of normalized propagation distance due to quantum contribution. The beam width parameter as a function of normalized propagation distance for various values of relative density parameter of the medium and intensity parameter has also been studied. The self-focusing is observed to be stronger with the increase in relative density parameter. Observation of early and strong self-focusing for higher values of relative density parameter and intensity parameter are reported. The present study might be very useful in the applications like the generation of inertial fusion energy driven by lasers, laser driven accelerators, scribing type of applications in electronics etc.

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1. Introduction

In the year 1962, Askar’yam [1] discovered the self-focusing effect of light. Hora [2], Siegrist [3] etc. have the remarkable contribution in the field of relativistic self-focusing of light. Thereafter, it attracts the attention of researcher and turn out to be most charming field of research. Researchers studied self-focusing of laser beam in plasma [2–4], cluster [5,6], liquid [7] etc. using various beam profiles like Gaussian beam [4], Hermite–Gaussian beam [8], cosh–Gaussian beam [9], Hermite-cosh-Gaussian beam [10–15] etc. Self-focusing of light has many socially useful applications like x-ray lasers and the laser driven charged particle accelerations [16], the generation of inertial fusion energy [17–19] etc. which makes the life of human being quite easier. Short pulse laser having high intensity of the order of $10^{17}$ – $10^{20}$\,W/cm\textsuperscript{2} enabled various high energy related experiments in the field of science and technology.

Self-focusing phenomenon in plasma arises as the laser light passes through the plasma and modifies the dielectric constant related to plasma. It may be relativistic or ponderomotive or thermal self-focusing in nature. Now a day, propagation of laser beam through cold plasma is widely studied by researcher because the quantum plasma systems have many useful applications. Rathore & Kumar [20], Kumar et al. [21], Bergamin [22] and many other researchers has studied nonlinear interaction in quantum plasma. Quantum plasma has high density and low temperature. Moreover, quantum plasma sys-
tems become more significant because of their relevance to laser–solid interactions, quantum dots [23], astrophysical and cosmological environments, [24,25] nanotechnology [26–28] and fusion-science [29,30]. In classical plasmas, Boltzmann–Maxwell statistical distribution is widely used while in the quantum plasmas, Fermi–Dirac statistical distribution is used and Wigner formalism is employed rather than classical Vlasov equation [31]. In classical regimes, all particles are considered as point-like particles as their de-Broglie wavelength is very small. However, if the de-Broglie wavelength in a regime becomes of the order of the average inter-particle distance, then quantum effect can be considered [32].

In the present case, relativistic self-focusing effect in cold plasma is studied. The high intensity laser pulses provide enough energy to the constituents like electrons in plasma which cause an electron oscillatory velocity in relativistic limits. Thus, the mass of electron oscillating at relativistic limit under laser field, increases by a factor given by $\gamma = 1 / \left(1 - v^2 / c^2 \right)^{1/2}$ and give rise to non-linearity which causes the relativistic self-focusing. Earlier, self-focusing in cold plasma has been studied by Jung et al. [33] The self-focusing of Gaussian laser beam in RCQ plasma has been studied by Patil et al. [34] and reported that a strong self-focusing of the beam occurs with the increase in the value of intensity parameter and relative density parameter due to the generation of quasi-static magnetic field. Habibi et al. [35] employed the density ramp profile to study the stationary self-focusing of intense laser beam in cold quantum plasma. Recently, Aggarwal et al. [40] presented the consideration of quantum effects for a stronger self-focusing with the combine effect of relativistic and ponderomotive nonlinearity.

In the present paper, the propagation of cosh-Gaussian beam in RCQ plasma has been studied. We have choose the cosh-Gaussian laser beam profile as cosh-Gaussian laser beam possesses more power than that of Gaussian laser beams having high intensity near the axis of propagation and hence, generates flat top beam profiles [36] which is useful for scribing type of applications in electronics where same intensity of laser beams for long time is required. Zhang et al. [37] has identified a group of virtual sources that generate a cosh-Gaussian wave. Previously, cosh-Gaussian profile has been studied by various authors viz. Gill et al. [9], Habibi & Ghamari [38] etc. We develop the equations for beam width parameter for cosh-Gaussian beam and solve them numerically by using Wentzel–Kramers–Brillouin (WKB) and Paraxial approximations [4,39] and observed the early enhancement of self-focusing of the laser beam with normalized propagation distance. This paper is planned as follows: we find the beam width parameter equation in section II, result is discussed in section III and a brief conclusion is given in section IV.

2. Evolution of beam width parameter

The electric field distribution of cosh-Gaussian laser beam in cold plasma and propagating along z-axis is as follow:

$$ E(r, z) = \frac{E_0}{f(z)} e^{\frac{r^2}{2b^2}} \left[ e^{-\left(\frac{r^2}{2b^2} \right)} + e^{-\left(\frac{r^2}{2b^2} + \frac{z^2}{a^2} \right)} \right] $$

(1)

here $E_0$ is the amplitude of cosh-Gaussian laser beam with a position centered at $r = z = 0$, $f(z)$ is the dimensionless beam width parameters, $r_0$ and $b$ are the spot size and decentered parameter of the beam.

The propagating beam spreads an oscillatory velocity, $\nu = \nu_0 + \omega_0 \gamma$, to the electrons. Here $e$, $m_0$ and $\omega$ are the charge on electron, rest mass of electron and angular frequency of incoming laser beam respectively, and $\gamma = (1 + \alpha EE^*)^{1/2}$ is the intensity dependent relativistic factor with $\alpha = e^2 / m_0 c^2 \omega^2$, here $c$ is the speed of light in vacuum. The intensity dependent dielectric constant for the non-linear medium is obtained by applying the approach adopted by Sodha et al. [4] and expressed as:

$$ \varepsilon = \varepsilon_0 + \psi(EE^*) $$

(2)

where $\varepsilon_0 = 1 - \omega_0^2 / \omega^2$, is linear component of the dielectric constant with $\omega_0$ as plasma frequency. For cold plasma the dielectric constant is obtained by applying the approach as applied by Jung and Murakami [33],

$$ \varepsilon_{rel} = 1 - \frac{\omega_0^2}{\gamma \omega^2} \left(1 - \frac{\delta q}{\gamma} \right)^{-1} $$

(3)

with $\delta q = 4 \pi^2 h^2 / m^2 \omega^2 \lambda^4$, where $h$ and $\lambda$ are the Planck’s constant and wavelength of incident laser beam respectively. The classical relativistic dielectric constant can be obtained easily by ignoring the quantum effect by setting the value of $\delta q$ as zero.

For isotropic, non conducting and non absorbing medium, the wave equation using Maxwell’s equations is expressed as:

$$ \nabla^2 \tilde{E} + \frac{\varepsilon}{c^2} \frac{\partial^2 \tilde{E}}{\partial t^2} + \nabla \left( \frac{\tilde{E}}{\varepsilon_0} \nabla (\varepsilon_0) \right) = 0 $$

(4)

For $1 / (K^2) \nabla^2 (\ln \kappa) \ast 1$, we get,

$$ \frac{\partial^2 \tilde{E}}{\partial z^2} + \frac{\partial^2 \tilde{E}}{\partial r^2} + \frac{1}{r} \frac{\partial \tilde{E}}{\partial r} + \frac{\varepsilon_0 \omega^2}{c^2} \tilde{E} = 0 $$

(5)
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