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Exploration of Temperature Range for Self-Focusing of Lowest-order Bessel-Gaussian Laser Beams in Plasma with Relativistic and Ponderomotive Regime

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Abstract. In the present paper, we have explored the temperature range for self-focusing of lowest-order Bessel-Gaussian laser beams in plasma by considering combined effect of relativistic and ponderomotive regime of interaction. The nonlinear differential equation for beam-width parameter is exploited under Wentzel-Kramers-Brillouin and paraxial approximations by using parabolic equation approach. Results of numerical computation are presented in the form of graphs and discussed. It is found that the temperature range for self-focusing of zeroth-order Bessel-Gaussian beams decreases, as transverse component of wave parameter increases up to certain limit. The temperature range for self focusing of Gaussian beam in the plasma with relativistic and ponderomotive regime is also deduced as a particular case.

INTRODUCTION

The propagation of intense laser beams in plasmas is widely employed in many theoretical and experimental studies due to its potential relevance in many applications [1], such as laser-driven inertial confinement fusion, wakefield acceleration, x-ray lasers, high harmonic generation etc. So, the propagation of laser beam up to several Rayleigh lengths is necessary in order to keep its efficient interaction with the plasma for feasibilities of some of these applications. It is well known that within the framework of laser-plasma interaction, many self-action effects have received considerable attention. The phenomenon of self-focusing is one of the important nonlinear optical self-action effects developed by Akhmanov *et al*.[2] for general nonlinear medium and extended by Sodha *et al*.[3] for plasmas. Self-focusing of laser beams is generally due to the modification of dielectric constant of plasma by high intensity of laser beam. This nonlinearity in dielectric constant is mainly due to the two dominating contributions. One of them is the increasing relativistic mass of electrons arising from the quiver motion due to the laser electric field. This leads to transverse gradient of the refractive index which results in decrease in the spot size of the beam. This is generally known as relativistic self-focusing [4]. The other contribution arises from the nonlinear electron density perturbations due to the ponderomotive force which is known as ponderomotive self-focusing [5]. However, together with relativistic nonlinearity, ponderomotive nonlinearity also becomes important [6]. Therefore, their combination effect significantly influences the laser beam propagation in plasma. The combined effect of relativistic and ponderomotive self-focusing has been presented in several studies [7-16] under different situations. Recently, Patil *et al*.[17-21] highlighted an influence of light absorption on self-focusing of laser beams in plasma with relativistic and ponderomotive regime.

In this paper, we intend to explore the temperature range for self-focusing of circularly symmetric lowest-order Bessel-Gaussian laser beams in plasma with relativistic and ponderomotive regime of interaction. This beams family

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was introduced by Gori *et al.*[22]. Polynkin *et al.*[23] have employed such beam to generate an extended plasma channels. We rely on the paraxial approach introduced by Akhmanov *et al.* [2] and its extension by Sodha *et al.*[3].

ANALYTICAL FORMULATION

In the present study, we consider the propagation of laser beam having Bessel-Gaussian profile in plasma along z direction, characterized by relativistic and ponderomotive regime of interaction. The electric field distribution of Bessel-Gaussian beams has the following form

$$E_0^{\nu}(r,z)=\frac{E_0}{f(z)}exp\left(-\frac{r^2}{2r_0^2 f^2(z)}\right)J_{\nu}\left(\frac{\mu r}{\sqrt{2}r_0 f(z)}\right)exp(i\nu\theta), \tag{1}$$

where, r, θ are the radial and azimuthal angle coordinates of cylindrical coordinate system, E_0 is the constant amplitude of the electric field, $J_{\nu}(\cdot)$ is the Bessel function of first kind of order ν , r_0 is the spot size of the laser beam at plane of incidence, i.e., at $z=0$, μ is the transverse component of wave parameter and $f(z)$ is the dimensionless beam-width parameter in paraxial region.

The effective dielectric function of the plasma with relativistic and ponderomotive regime, takes the form [10]

$$\varepsilon = 1-\frac{exp[-\beta_0(\gamma-1)]}{\gamma}\ , \tag{2}$$

where $\beta_0 = m_0c^2/T$ and $\gamma = (1+\alpha EE^*)^{1/2}$ is the Lorentz relativistic factor with $\alpha = e^2/m_0^2\omega^2c^2$ as the coefficient of relativistic nonlinearity. Here e and m_0 are the charge and rest mass of electron; respectively, ω is the frequency of laser beam and c is the speed of light in free space. Eq.(2) can be written as [3]

$$\varepsilon = \varepsilon_0 + \phi(EE^*) \tag{3}$$

where, ε_0 and ϕ are the linear and nonlinear parts of the dielectric function respectively.

The electric field E of the beam in plasmas with ε given by Eq. (3) satisfies the wave equation as

$$\nabla^2 E + \frac{\omega^2}{c^2}\varepsilon E = 0 \tag{4}$$

If we introduced $E = A(r,z)exp(-ik_0 z)$ in Eq.(4), where $A(r,z)$ is the complex function of its argument and can be described by the parabolic equation in the WKB approximation as

$$2ik_0\frac{\partial A}{\partial z} + \nabla_{\perp}^2 A + \frac{\omega^2}{c^2}\phi(EE^*)A = 0 \tag{5}$$

Within the framework paraxial approximation, the intensity distribution of Bessel-Gaussian laser beam propagating along z axis is given by

$$A_0^{\nu}A_0^{\nu^*} = \frac{E_0^2}{f^2(z)}exp\left(-\frac{r^2}{r_0^2 f^2(z)}\right)J_{\nu}^2\left(\frac{\mu r}{\sqrt{2}r_0 f(z)}\right), \tag{6}$$

Following the approach given by Akhmanov *et al.*[2] and its extension by Sodha *et al.*[3], the dimensionless beam-width parameter f for zeroth-order Bessel-Gaussian beams is obtained as

$$\frac{d^2 f}{d\eta^2} = \frac{(2+\mu^2)}{2f^3} - \frac{\rho_0^2(4+\mu^2)}{8f^3}\frac{X(1+Y)exp(\beta_0 - Y)}{U^3} \tag{7}$$

where $X = \alpha E_0^2$, $Y = \beta_0 U$, $U = (1+G)^{1/2}$ and $G = X/f^2$, $\eta = z/R_d$ is the dimensionless distance of propagation, $R_d = k_0 r_0^2$ is the Rayleigh length, and $\rho_0 = r_0\omega_p/c$ is the normalized equilibrium beam radius,.

At initially plane wavefront of the zeroth-order Bessel-Gaussian beams, i.e., at $\eta = 0$, $f=1$ and $df/d\eta = 0$. The condition $d^2f/d\eta^2 = 0$, leads to the propagation of zeroth-order Bessel-Gaussian beams without convergence or divergence (called also the self-trapped mode). This condition is known as critical condition. Thus by putting $d^2f/d\eta^2 = 0$ in Eq. (7), we obtain a relation for ρ_0 as

$$\rho_0^2 = \frac{\left(4+2\mu^2\right)U^3}{\left(4+\mu^2\right)X\left(1+Y\right)exp\left(\beta_0 - Y\right)}. \tag{8}$$

NUMERICAL RESULTS AND DISCUSSION

Equation (7) describes the dependence of dimensionless beam-width parameter f with dimensionless distance of propagation η in plasma with combined effect of relativistic and ponderomotive regime of interaction. Eq.(8) expresses the required initial conditions for the self-trapping mode of the propagation. Bokaei *et al*.[10] investigated the temperature range in the competition between relativistic and ponderomotive effects in self-focusing of Gaussian laser beam in plasma. Their results indicate that there is a temperature interval in which self-focusing occurs, while beam diverges outside of this region. In addition, their results represent an existence of the turning point temperature values for which self-trapping occurs. By setting initial conditions; i.e., $\alpha E_0^2 = 0.15$, $r_0 = 20\ \mu m$, $n_0 = 2.6\times 10^{17}\ cm^{-3}$, $\rho_0 = 1.92$, the turning point temperature values for Gaussian beam propagation in plasma are $T = 20\ KeV$ and $T = 100\ KeV$. Considering same initial conditions, dependence of transverse component of wave parameter μ as a function of plasma electron temperature T is depicted in Fig.1.

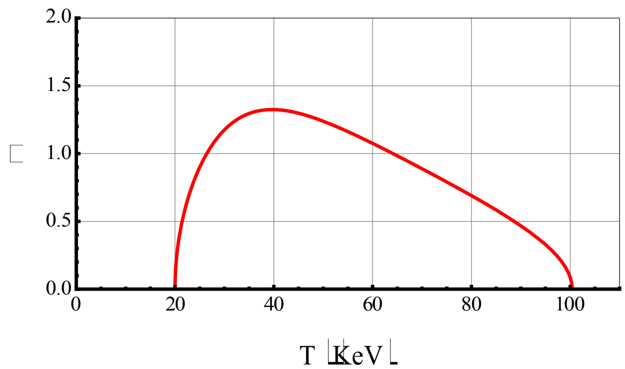

FIGURE 1. Variation of transverse component of wave parameter μ as a function of plasma electron temperature T.

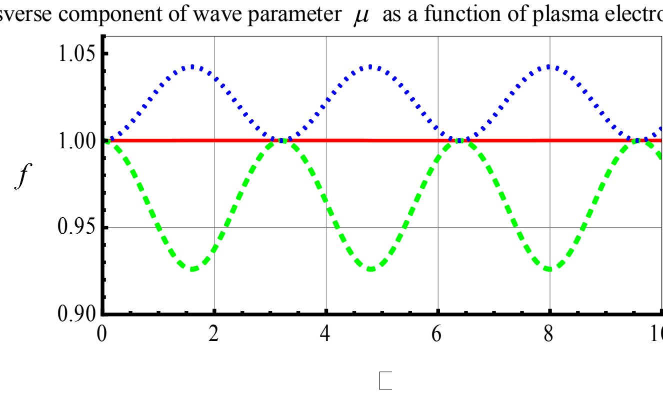

FIGURE 2. Variation of beam-width parameter f as a function of dimensionless distance of propagation η. Solid line corresponds to any point on the critical curve of Fig.1, dashed curve corresponds to a point (40, 1) below the critical curve of Fig. 1 and dotted curve corresponds to a point (40, 1.5) above the critical curve of Fig. 1.

From this figure it is clear that μ has certain limit for self-focusing of Bessel-Gaussian laser beams in plasmas. It is also found that the temperature range for self-focusing of Bessel-Gaussian beams decreases, as μ increases up to such limit. It is interesting to note that for Gaussian beam ($\mu = 0$), $T = 20\ KeV$ and $T = 100\ KeV$ are the turning points. Within this temperature range, self-focusing can occur as pointed out by Bokaei *et al*.[10] for Gaussian beam. If the point lies inside (outside) the area under the curve of Fig.1, beam will display self-focusing (defocusing). If the point lies on the curve of Fig. 1, beam will find self-trapped mode without convergence or divergence. Fig. 2 present the variation of beam-width parameter f with dimensionless distance of propagation η for representative points as explained above.

CONCLUSION

In conclusion, propagation dynamics of lowest-order Bessel-Gaussian laser beams in plasma with relativistic ponderomotive regime of interaction characterized by self-focusing, defocusing and self-trapping is explored. The temperature range for self-focusing of zeroth-order Bessel-Gaussian beams is highlighted. The present study is the generalization of some previous works. Consequently, from our results, the temperature range for self-focusing of Gaussian beams in the plasma is deduced as a particular case.

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