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B. D. Vhanmore, A. T. Valkunde, T. U. Urunkar, K. M. Gavade, S. D. Patil, and M. V. Takale

Self-Focusing of Asymmetric Cosh-Gaussian Laser Beams in Weakly Ionized Collisional Magnetized Plasma

B. D. Vhanmore[1], A. T. Valkunde[1,2], T. U. Urunkar[1], K. M. Gavade[1], S. D. Patil[3,a)], and M. V. Takale[1,b)]

[1]*Department of Physics, Shivaji University, Kolhapur 416 004, Maharashtra, India*
[2]*Department of Physics, Government Polytechnic, Khamgaon, Buldhana, 444 312, Maharashtra, India*
[3]*Department of Physics, Devchand College, Arjunnagar, Kolhapur 591 237, Maharashtra, India*

[a)]Corresponding author: sdpatilphy@gmail.com
[b)]mvtphyunishivaji@gmail.com

Abstract. In the present paper, we have exploited the self-focusing of asymmetric cosh-Gaussian (ChG) laser beams in weakly ionized collisional magnetized plasma. Differential equations for the beam-width parameters in two transverse dimensions of the beam are obtained by using Wentzel-Kramers-Brillouin (WKB) and paraxial approximations through parabolic equation approach. The final results of numerical computation are presented in the form of graphs and discussed. It is found that enhanced self-focusing is observed with reduction in self-focusing length by increasing the decentred parameters in both the dimensions of the beam.

INTRODUCTION

The nonlinear interaction of high intensity lasers with plasma is very interesting due to its potential relevance to many applications [1] such as laser-driven inertial confinement fusion, wakefield acceleration, x-ray lasers, high harmonic generation etc. So, an understanding of laser-plasma interaction is crucial in the design of an evaluation of targets for laser-driven fusion and other potential applications. For feasibility of some of these applications, the guided laser beam should propagate over several Rayleigh lengths by efficient interaction with plasmas without loss of the energy. Amongst various self-action effects in plasmas, the phenomenon of self-focusing [2] is genuinely a nonlinear optical effect induced by modification of dielectric constant of plasma due to the intense laser field. The self-focusing of laser beams having non-uniform distribution of irradiance in a plane, normal to direction of propagation leads to non-uniform distribution of carriers along the wavefront, which further leads to a change in dielectric constant of plasma [3].

In collisional plasma, the focusing of laser beams is due to a non-uniform profile of the dielectric function on account of non-uniform ohmic heating energy lost by electrons due to collisions or thermal conduction [4]. If the wave frequency of interest ω is larger than the electron collision frequency ν, the plasma can be said to be collisional plasma. Self-focusing of laser beams in collisional plasmas has been a very important branch of laser-plasma interaction. Elegant reviews of this phenomenon have been furnished by Sodha et al.[3] and Sprangle *et al.*[5]. In theoretical studies of an interaction of lasers with collisional plasmas, superthermal electrons generation [6], transport in fast ignition [7], absorption of laser light [8], filamentation instability [9], etc. have been explored. On experimental side, the dynamics of dense laboratory plasma jet [10] using laser beam have been conducted.

Most of the analyses [11-15] on propagation of laser beams in plasmas are devoted to the Gaussian beams. Few studies [16-27] have been evinced in the propagation of high power decentred Gaussian laser beams in plasmas and their self-focusing/defocusing effect. The aim of this paper is to study the self-focusing of asymmetric cosh-Gaussian laser beams in weakly ionized collisional magnetized plasma by employing WKB and paraxial approximations through usual parabolic equation approach [2, 3]. We have done theoretical study concerned with

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beam-width parameter changes which are related to the transverse dimensions of the beam during the propagation through plasma.

SELF-FOCUSING

We consider the propagation of asymmetric cosh-Gaussian laser beams through plasma along the z-direction, which is also the direction of the static magnetic field. Under WKB approximation, the parabolic equation to be solved for right circularly polarized mode (called also the extraordinary mode) of laser for magnetized plasma, is given as [28]

$$-2ik_+\frac{\partial A_+}{\partial z}+\frac{1}{2}\left(1+\frac{\varepsilon_{0+}}{\varepsilon_{0zz}}\right)\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}\right)A_+ +\frac{\omega^2}{c^2}\Phi_+(A_+A_+^*)A_+=0\,, \tag{1}$$

where, ε_{0+} and $\Phi_+(A_+A_+^*)$ are the respective linear and nonlinear parts of effective dielectric function of ε_+ which can, in general, be expressed as [3]

$$\varepsilon_+=\varepsilon_{0+}+\Phi_+\left(A_+A_+^*\right). \tag{2}$$

In case of weakly ionized collisional magnetized plasma, ε_{0+} and Φ_+ is expressed as [29]

$$\varepsilon_{0+}=1-\frac{\omega_p}{\omega(\omega-\omega_c)}, \tag{3}$$

$$\Phi_+\left(A_+A_+^*\right)=\frac{\omega_p}{\omega(\omega-\omega_c)}\frac{\alpha\, A_+A_+^*}{4\left(1-\omega_c/\omega\right)^2+\alpha\, A_+A_+^*}\ , \tag{4}$$

where $\omega_p=\left(4\pi\, n_0e^2/m\right)^{1/2}$ and $\omega_c=eB_0/mc$ are the electron plasma frequency and cyclotron frequency, respectively and rest of the symbols carry their defined meanings [3].

Taking $A_+=A_{0+}(x,y,z)\exp[-ik_+S(x,y,z)]$, the solutions for A_{0+}^2 and S in the paraxial approximation for initially ChG beams can be written as

$$A_{0+}^2=\frac{E_{0+}^2}{f_{1+}f_{2+}}\left\{\cosh\left(\frac{b_1x}{r_{0+}f_{1+}}\right)\cosh\left(\frac{b_2y}{r_{0+}f_{2+}}\right)\right\}^2, \tag{5}$$

$$S_+=\frac{1}{\left(1+\varepsilon_{0+}/\varepsilon_{0zz}\right)}\left(\frac{x^2}{f_{1+}}\frac{df_{1+}}{dz}+\frac{y^2}{f_{2+}}\frac{df_{2+}}{dz}\right)+\psi_+(z), \tag{6}$$

where E_{0+} is the initial amplitude of laser with initial beam-width r_{0+}, b_1 and b_2 are the decentred parameters of ChG beams with f_{1+} and f_{2+} as the corresponding beam-width parameters in x and y dimensions respectively.

Following the approach of Akhmanov *et al.*[2] and its extension by Sodha *et al.*[3], the beam-width parameter differential equations for ChG beams in weakly ionized collisional magnetized plasma are obtained as

$$\frac{d^2f_{1+}}{d\zeta^2}=\frac{A_1}{2}\frac{\delta_+^2}{f_{1+}^3}+\frac{B_1\,\delta_+\rho_{0+}^2p_{0+}\omega(\omega-\omega_c)\,\omega_p^2}{f_{1+}\left[p_{0+}^2\omega^2+4f_{1+}f_{2+}(\omega-\omega_c)^2\right]^2}, \tag{7}$$

$$\frac{d^2f_{2+}}{d\zeta^2}=\frac{A_2}{2}\frac{\delta_+^2}{f_{2+}^3}+\frac{B_2\,\delta_+\rho_{0+}^2p_{0+}\omega(\omega-\omega_c)\,\omega_p^2}{f_{2+}\left[p_{0+}^2\omega^2+4f_{2+}f_{1+}(\omega-\omega_c)^2\right]^2}, \tag{8}$$

where $A_{1,2}=4\left(1-b_{1,2}^2\right)$, $B_{1,2}=b_{1,2}^2-2$, $p_{0+}=\alpha E_{0+}^2$ and $\rho_{0+}=r_{0+}\omega/c$ is the equilibrium beam radius, $\zeta=z/k_+r_{0+}^2$ is the dimensionless distance of propagation.

For an initially plane wavefront, $df_{1+,2+}/d\zeta=0$ and $f_{1+,2+}=1$ at $\zeta=0$, the conditions $d^2f_{1+,2+}/d\zeta^2=0$, leads to the propagation of ChG beams without convergence or divergence (called also the self-trapped mode). These conditions are known as critical conditions. Thus by putting $d^2f_{1+,2+}/d\zeta^2=0$ in Eqs. (7) and (8), we obtain a relations for ρ_{01+} and ρ_{02+} as

$$\rho_{01+}^2 = -\frac{A_1\delta_+\left[p_{0+}^2\omega^2 + 4(\omega-\omega_c)^2\right]^2}{2B_1\ p_{0+}\omega(\omega-\omega_c)\omega_p^2}, \tag{9}$$

$$\rho_{02+}^2 = -\frac{A_2\delta_+\left[p_{0+}^2\omega^2 + 4(\omega-\omega_c)^2\right]^2}{2B_2\ p_{0+}\omega(\omega-\omega_c)\omega_p^2}. \tag{10}$$

NUMERICAL RESULTS AND DISCUSSION

Equations (7) and (8) are the nonlinear coupled differential equations governing self-focusing of ChG beams in weakly ionized collisional magnetized plasma. First term on the right-hand sides of these equations leads to divergence of the laser beam, while the second term is responsible for self-focusing of the beam. We have solved these equations simultaneously by using fourth-order Runge-Kutta method under the initial conditions at $\zeta = 0$, $f_{1+,2+} = 1$ and $d^2 f_{1+,2+}/d\zeta = 0$. The requisite laser-plasma parameters are: $\omega = 1.778\times10^{14}\ rad/s$, $n_0 = 10^{19}\ cm^{-3}$, $B_0 = 0.1MG$, $b_{1,2} = 0.0-0.5$, $\rho_{01+,02+} = 2.6$ and $p_{0+} = 3$.

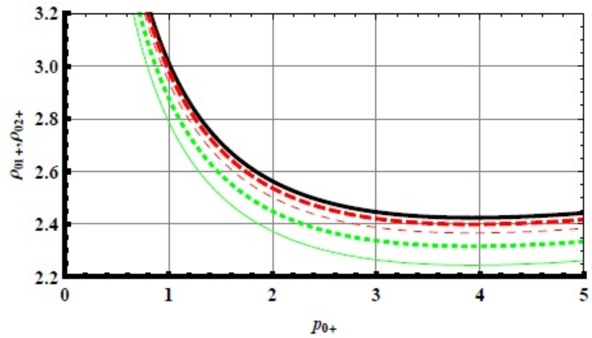

FIGURE 1. Variation of equilibrium beam radius $\rho_{01+,02+}$ with initial intensity parameter p_{0+} for different decentred parameters b_1 and b_2. $b_{1,2} = 0.0$ (solid curves), $b_1 = 0.2$ and $b_2 = 0.3$ (dashed curves), $b_1 = 0.4$ and $b_2 = 0.5$ (dotted curves). Thick curves are for ρ_{01+} and thin curves are for ρ_{02+}. Other parameters are: $\omega = 1.778\times10^{14}\ rad/s$, $n_0 = 10^{19}\ cm^{-3}$, $B_0 = 0.1MG$.

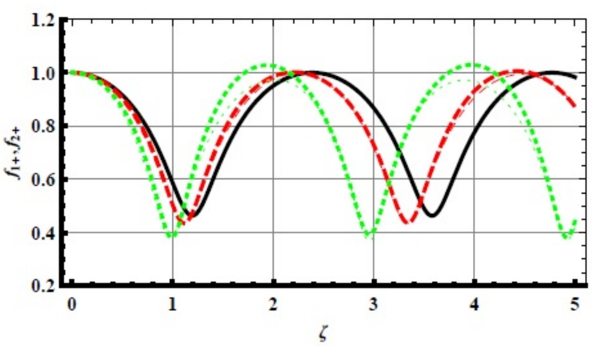

FIGURE 2. Variation of beam-width parameters f_{1+} and f_{2+} as a function of ζ for different decentred parameters b_1 and b_2 with, $\rho_{01+,02+} = 2.6$ and $p_{0+} = 3$. $b_{1,2} = 0.0$ (Solid curves), $b_1 = 0.2$ and $b_2 = 0.3$ (dashed curves), $b_1 = 0.4$ and $b_2 = 0.5$ (dotted curves). Thick curves are for f_{1+} and thin curves are for f_{2+}. Other parameters are same as that of in Fig. 1

Fig. 1 shows the critical curves for ChG beams with different decentred parameters b_1 and b_2 in x and y dimensions of the beam. It is noticed from this figure that the values of ρ_{01+} and ρ_{02+} with intensity parameter p_{0+}

decreases initially and slowly attains a constant value with increase in b_1 and b_2. It is also clear that asymmetry in b_1 and b_2 values gives unsynchronized respective critical curves. This indicates that the ChG beam is circularly symmetric for identical b values along both transverse dimensions. Fig. 2 describes the variation of f_{1+} and f_{2+} as a function of ζ for $\rho_{01+,02+} = 2.6$ and $p_{0+} = 3$ with same values of b_1 and b_2 as in Fig. 1. It is obvious from the figure that, for symmetric $b_{1,2}$ values, f_{1+} and f_{2+} overlap with each other, while for asymmetric values of $b_{1,2}$, f_{1+} along x and f_{2+} along y direction are propagate separately. From figure, it is also observed that with increase in decentred parameters in either dimensions of the beam, enhanced self-focusing is observed with reduction in self-focusing length. These results may be helpful for understanding many applications related to laser-plasma interaction where decentred irradiance distribution of the beam plays vital role.

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