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On the Exploration of Effect of Critical Beam Power on the Propagation of Gaussian Laser Beam in Collisionless Magnetized Plasma

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Abstract. It is quite known that critical power of the laser plays vital role in the propagation of Gaussian laser beam in collisionless plasma. The nonlinearity in dielectric constant considered herein is due to the ponderomotive force. In the present analysis, the interval of critical beam power has been explored to sustain the competition between diffraction and self-focusing of Gaussian laser beam during propagation in collisionless magnetized plasma. Differential equation for beam-width parameter has been established by using WKB and paraxial approximations under parabolic equation approach. The effect of critical power on the propagation of Gaussian laser beam has been presented graphically and discussed.

INTRODUCTION

The interactions of high intensity laser beam with plasma has been a subject of fascinating field of research due to its relevance to wide ranging applications such as laser particle acceleration [1, 2], fast ignition for inertial confinement fusion [3, 4] etc. In plasmas, the self-focusing of laser beams [5] is very important because it affects other nonlinear phenomena. In general, three main nonlinearities [6], viz., relativistic, ponderomotive, and collisional are operative during the interaction lasers with plasmas. The study of these nonlinearities in the self-focusing of the beams has received considerable interest in the last 50 years. In case of collisionless plasma, at moderate fields of laser beam, there is a modification of electron density due to ponderomotive force. Subsequently the dielectric function of the plasma is altered causing self-focusing /defocusing of the beam [6]. Combined effect [7, 8, 9, 10] of relativistic and ponderomotive nonlinearities is also explored in the interaction of laser beams with plasmas.

In the analysis of self-focusing of laser beams, a paraxial approach developed by Akhmanov et al. [5] and extended by Sodha et al. [6] is more popular and extensively employed. It is to be noted that amongst the various laser beam profiles with transverse irradiance distribution, a fundamental (Gaussian) laser beam has a wide range of practical applications [11]. It is commonly utilized in theoretical studies of steady-state self-focusing, because its use simplifies the mathematical complexity of the problem and provides a resonably accurate interpretation of the relevant experimental findings. Such beam also plays a vital role in various nonlinear effects on account of its specific characteristics such as small beam divergence, high degree of coherence, great spectral purity etc. As such in most of the theoretical studies [12, 13, 14] on self-focusing of laser beams in plasmas, a Gaussian beam have been extensively taken into consideration.

In the present work, authors have explored effect of critical beam power on self-focusing of Gaussian laser beam in collisionless magnetized plasma by considering ponderomotive nonlinearity. We have done theoretical study based on WKB and paraxial approximations under usual parabolic equation approach [5, 6]

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THEORETICAL FRAMEWORK

The nonlinear wave equation governing the the evolution of the electric field in magnetized plasma for right handed circularly polarized (extraordinary mode) of the laser can be expressed as [15]

$$\frac{\partial^2 E_+}{\partial z^2} - 2ik_+\frac{\partial E_+}{\partial z} + \delta_+\left(\frac{\partial^2}{\partial r^2} + \frac{1}{r}\frac{\partial}{\partial r}\right)E_+ + \frac{\omega^2}{c^2}(\epsilon_+ - \epsilon_{0+})E_+ = 0, \tag{1}$$

where, $\delta_+ = \frac{1}{2}(1 - \frac{\varepsilon_{0+}}{\varepsilon_{0zz}})$ with $\varepsilon_{0zz} = 1 - \frac{\omega_p^2}{\omega^2}$. The effective dielectric function ϵ_+ of the plasma can be expressed as [6]

$$\varepsilon_+ = \varepsilon_{0+} + \phi(E_+E_+^*), \tag{2}$$

where, ε_{0+} and $\phi(E_+E_+^*)$ are the linear and nonlinear part of ε_+, respectively with

$$\varepsilon_{0+} = 1 - \frac{\omega_p^2}{\omega(\omega - \omega_c)}, \tag{3}$$

$$\phi(E_+E_+^*) = \frac{\omega_p^2}{2\omega(\omega - \omega_c)}[1 - exp(-\alpha E_{0+}^2), \tag{4}$$

where $\omega_p = (4\pi N_0 e^2/\ m)^2$ is the plasma frequency, $\omega_c =\ eB_0/\ mc$ is cyclotron frequency, e and m are the electronic charge and its rest mass respectively, $\alpha = 3m\alpha_0/4M$, with $\alpha_0 = e^2/6m\omega^2 k_B T_0$, N_0 is the unperturbed density of plasma electrons, m is the mass of ion, ω is the angular frequency of laser used, K_B is the Boltzmann constant, B_0 is static magnetic field and T_0 is equilibrium plasma temperature.

For $z > 0$, one can assume an energy conserving Gaussian ansatz for the laser intensity as [6]

$$A_{0+}^2 = \frac{E_{0+}^2}{f_+^2} exp\left(\frac{-r^2}{r_{0+}^2 f_+^2}\right), \tag{5}$$

where E_{0+} is an initial amplitude of Gaussian laser beam with initial beam-width r_{0+} and f_+ is the dimensionless beam width parameter.

Following approach given by Akhmanov et al. [5] and developed by Sodha et al. [6], we have obtained the dimensionless beam-width parameters f_+ for extraordinary mode of the laser as,

$$\frac{\partial^2 f_+}{\partial \zeta^2} = \frac{1}{\varepsilon_{0+}}\frac{1}{f_+^3}\left\{\frac{12\delta_+^2}{3} - \frac{\rho_+^2 exp(-p_+)p_+\gamma_+\delta_+}{2}\right\}, \tag{6}$$

where $\Omega_p = \frac{\omega_p}{\omega}$, $\Omega_c = \frac{\omega_c}{\omega}$, $\gamma_+ = \frac{\Omega_p^2}{1-\Omega_c}$, $p_+ = \frac{\alpha E_{0+}^2}{f_+^2}$, $\rho_+ = \frac{r_{0+}\omega}{c}$. The quantity p_+ is the beam power and $\zeta = z/k_+ r_{0+}^2$ is the normalized distance of propagation.

DISCUSSION AND CONCLUSION

Equation (6) is second order nonlinear differential equation which gives evolution of a laser beam during propagation to collisionless magnetized plasma. The first term on right-hand side of this equation corresponds to the diffraction divergence of the beam while second term corresponds to the convergence resulting from the ponderomotive nonlinearity in dielectric constant of magnetized plasma. By subjecting Eq.(6) under critical condition, the general power of laser beam p_+ is replaced by critical power. Therefore the right-hand side of Eq.(6) takes the form

$$F(p_{0+}) = \left\{\frac{12\delta_+^2}{3} - \frac{\rho_{0+}^2 exp[-p_{0+}]p_{0+}\gamma_+\delta_+}{2}\right\} \tag{7}$$

where, ρ_{0+} and p_{0+} corresponds to critical values of ρ_{0+} and p_{0+} respectively. By reducing defining equations for δ_+ and γ_+ numerically with the help of laser-plasma parameters; $N_0 = 1 \times 10^{18} cm^{-3}$, $\omega = 1.776 \times 10^{15} rad/s$, $B_0 = 1MG$, Eq.(7) throws light on the dependence of $F(p_{0+})$ on critical power p_{0+} of the laser beam as

$$F(p_{0+}) = 3.88966 - 1168.72 exp[-p_{0+}]p_{0+} \tag{8}$$

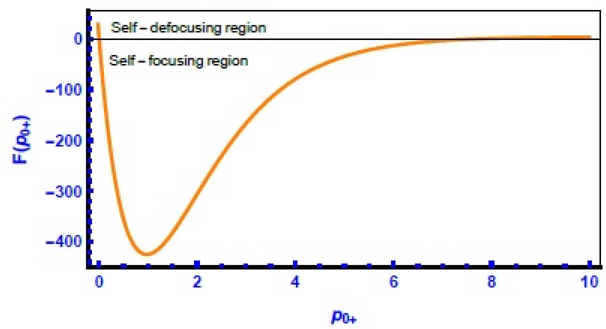

FIGURE 1. Variation of $F(p_{0+}$ as a function of critical power p_{0+}.

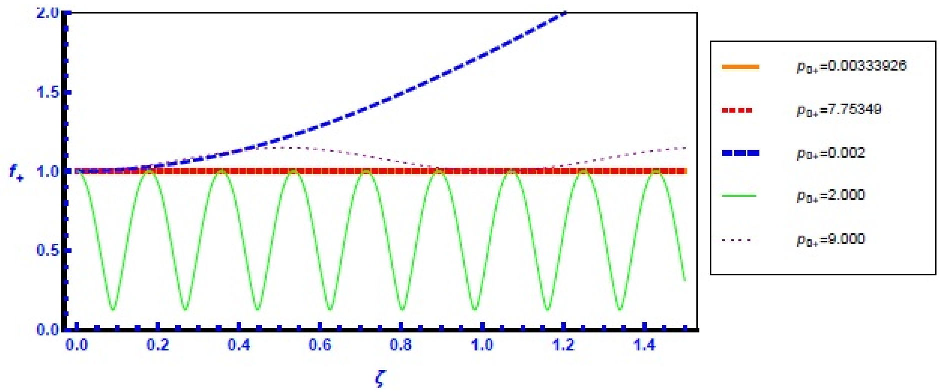

FIGURE 2. Variation of beam-width parameter f_+ with dimensionless distance of propagation ζ in collisionless magnetized plasma.

To explore the effect of critical power right at the beginning one has to pay little attention to plot shown in Fig.1. The plot can be conveniently studied for three distinct conditions.

Self-trapping:

$$F(p_{0+}) = 0 \text{ for } p_{0+} = 0.000333926 \text{ and } p_{0+} = 7.75349$$

Self-defocusing:

$$F(p_{0+}) > 0 \text{ for } 7.75349 < p_{0+} < 0.000333926$$

Self-focusing:

$$F(p_{0+}) < 0 \text{ for } 0.000333926 < p_{0+} < 7.75349$$

The simple analytical approach leads to following limits for critical beam power is depicted in Fig.1. The limits of critical power investigated in above conditions can support the graph of beam width parameter f_+ versus normalized propagation distance ζ as shown in Fig.2. From fig.2 the steady state defocusing of beam is observed for $p_{0+} < 0.000333926$ and for $p_{0+} > 7.75349$ the beam undergoes oscillatory defocusing. The beam propagates without convergence or divergence i.e., in uniform wave-guide mode (self-trapped mode) at exact values $p_{0+} = 0.000333926$ and $p_{0+} = 7.75349$. It is also evident from fig.2 that oscillatory self-focusing is observed for $0.000333926 < p_{0+} < 7.75349$. Such stationary oscillatory self-focusing character of Gaussian beam has been already reported in earlier studies at different situations [14, 16, 17, 18]. In conclusion, it is observed that the our investigation shows that pre-conditioning of a critical power at the beginning of propagation can determine propagation dynamics effectively.

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