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Effect of exponential density transition on self-focusing of q-Gaussian laser beam in collisionless plasma

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Abstract. In this work, nonlinear aspects of a high intensity q-Gaussian laser beam propagating in collisionless plasma having upward density ramp of exponential profiles is studied. We have employed the nonlinearity in dielectric function of plasma by considering ponderomotive nonlinearity. The differential equation governing the dimensionless beam width parameter is achieved by using Wentzel-Kramers-Brillouin (WKB) and paraxial approximations and solved it numerically by using Runge-Kutta fourth order method. Effect of exponential density ramp profile on self-focusing of q-Gaussian laser beam for various values of q is systematically carried out and compared with results Gaussian laser beam propagating in collisionless plasma having uniform density. It is found that exponential plasma density ramp causes the laser beam to become more focused and gives reasonably interesting results.

INTRODUCTION

High intense laser beam and plasma interaction experiments reveals variety of phenomena which are important in many applications,[1, 2, 3, 4, 5] such as self-phase modulation, high harmonic generation, x-ray lasers, laser-driven fusion, laser based plasma accelerators, and, soft x-ray generation etc.When an intense laser beam propagate through the plasma, it changes dielectric properties of plasma medium. Self-focusing describes in general focusing of the laser beam by itself as a result of the nonlinear refractive index induced by the beam itself.[6]

Various laser beam profile have variation in the intensity along its wave front. Electrons in the plasma experiences ponderomotive force arising from the gradient of the non-uniform irradiance. This force pushes electrons away from the axis region where the laser beam is more intense. Thus expulsive force is created inside the channel, plasma pressure outside the channel balances this exulsive force which results lowered density in the channel. Thus effective dielectric function of get modified significantly, this self-induced nonlinearity in dielectric constant of plasma gives rise to nonlinear effects such as self-focusing and defocusing.[7]

In recent years, a considerable interest has been evinced for slowly increasing plasma density ramp to overcome the diffraction and guiding the laser beam over long distance. There are lot of work had been carried with different density ramp profiles,[8, 9, 10, 11, 12] in which tangent density ramp profile has been studied extensively due to its upward increasing nature. In this paper new exponential density ramp profile of the form $n = n_0 exp(\xi/d)$ have been introduced, such type of ramp profile has been suggested by Sharma et al.[13]. Most of study of laser plasma interaction have been carried out under the assumption that the intensity distribution of laser beam have a Gaussian nature[14, 15, 16]. However, Patel et al.[17] reported that the intensity profile of the laser beam shows deviations from Gaussian profile and suggested that the beam intensity distribution can welly characterized by q-Gaussian distribution of the form $f(r) = f(0)\left(1 + \frac{r^2}{q{r_0}^2}\right)^{-q}$. When q→ ∞ the profile of a q-Gaussian laser beam gradually converges to a Gaussian profile. The aim of this paper is investigate effect of exponential density ramp and various values q on self-focusing of q-Gaussian laser beam in collisionless plasma. As usual, present analysis employs parabolic equation approach under WKB and paraxial approximations.

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SELF-FOCUSING

Here we are considering propagation of laser beam into the plasma along z direction, starting from $z = 0$.

$$E = A(r,z)exp[i(\omega t - k_0 z)], \tag{1}$$

where, $k_0 = \frac{\omega}{c}\sqrt{\varepsilon_0}$ is wave number in the absence of plasma density transition and ω is frequency of laser used.

The wave equation governing the electric field vector of a laser beam in plasma medium with effective dielectric function ε in cylindrical coordinate system can be written as

$$\frac{\partial^2 \vec{E}}{\partial z^2} + \frac{\partial^2 \vec{E}}{\partial r^2} + \frac{1}{r}\frac{\partial \vec{E}}{\partial r} + \frac{\omega^2}{c^2}\varepsilon \vec{E} = 0. \tag{2}$$

The effective dielectric function of plasma can also be written as[18]

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

where, $\varepsilon_0 = 1-(\omega_p^2/\omega^2)$ is the linear part of dielectric constant with $\omega_p = (4\pi ne^2/m)^{1/2}$ as the plasma frequency. Here e and m are the electronic charge and its rest mass respectively. The perturbed electron density n is given by

$$n = n_0 exp\left(\frac{z}{dR_d}\right), \tag{4}$$

where, n_0 is the equilibrium electron density, $R_d = kr_o{}^2$ is diffraction length with $k = \frac{\omega}{c}\sqrt{\varepsilon}$ is the wave number in presence of plasma density transition and d is adjustable dimensionless parameter. Second term in Equation 3, the intensity dependent part of dielectric constant for collisionless plasma is given by,

$$\phi(EE^*) = \frac{\omega_p^2}{\omega^2}\left[1 - exp\left(-\frac{3m\alpha EE^*}{4M}\right)\right], \tag{5}$$

with

$$\alpha = \left(\frac{e^2 M}{6k_B T_0 \omega^2 m^2}\right)$$

where, m, M, k_0 and T_0 are mass of electron, mass of ion, Boltzmann constant and equilibrium temperature of plasma respectively. We now introduce eikonal S as,

$$A = A_0(r,z)exp[ikS(r,z)], \tag{6}$$

where,$A_0(r,z)$ and $S(r,z)$ are real function of r and z with,

$$S = \frac{r^2}{2}\beta(z) + \phi(z), \tag{7}$$

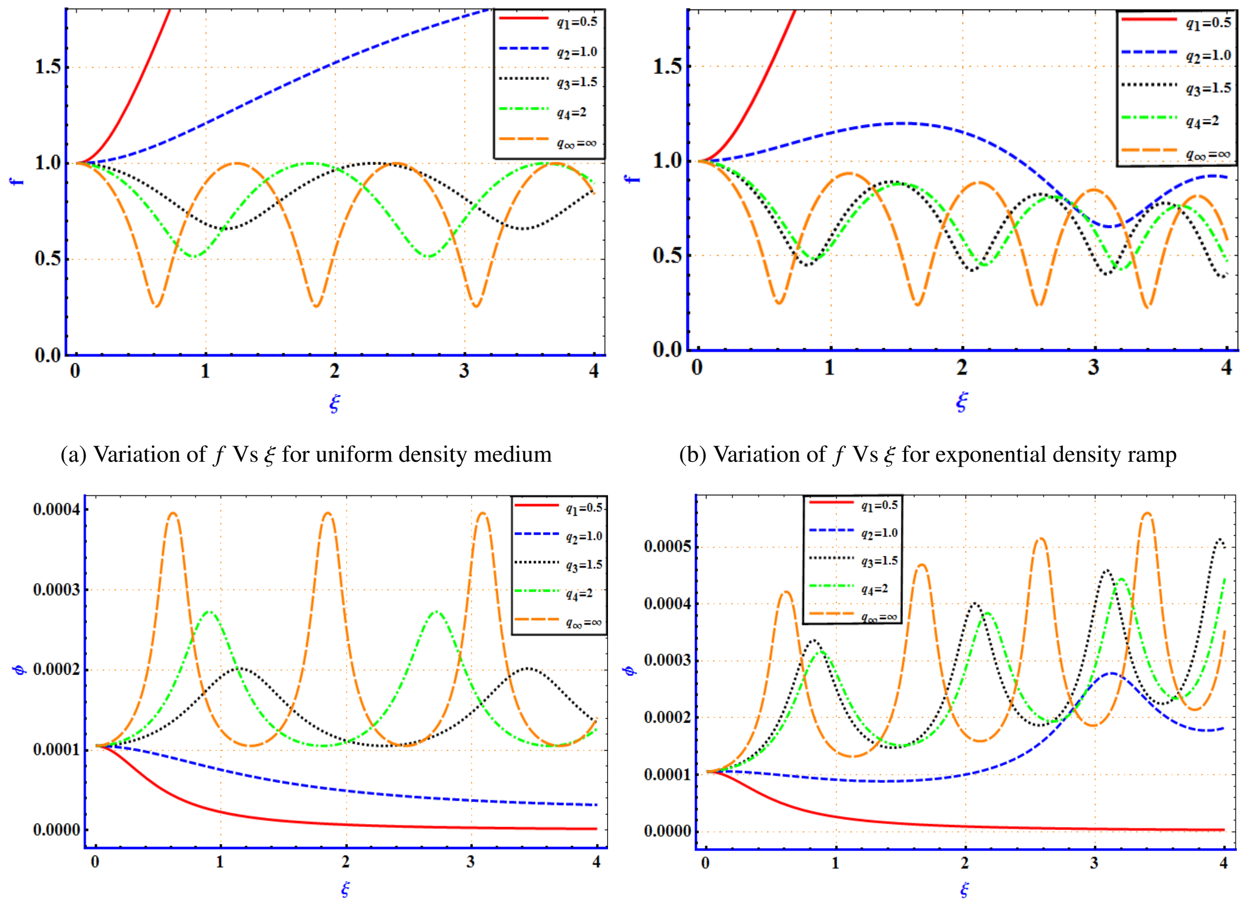
where $\beta(z)$ can be expressed as $(1/f)(\partial f/\partial z)$ and it represent the reciprocal of curvature of the wave front and $\phi(z)$ is phase shift. For incident q-Gaussian laser beam we write,

$$A_0^2 = \frac{E_0^2}{f^2}\left(1 + \frac{r^2}{qr_0^2 f^2}\right)^{-q}, \tag{8}$$

where, f is beam width parameter which is measure of both axial intensity and width of the beam and r_0 is initial radius of laser beam. Following the approach given by Akhomonov et al.[19] and devoloped by Sodha et al.[18], we have obtained nonlinear differential equation in presence of exponential density ramp profile as,

$$\left(1 - \frac{\xi\omega_{p0}^2 exp\left(\frac{\xi}{d}\right)}{2d\omega^2\left(1 - \frac{\omega_{p0}^2}{\omega^2}exp\left(\frac{\xi}{d}\right)\right)}\right)\frac{d^2 f}{d\xi^2} = \frac{4+q}{qf^3} - \frac{3m\alpha E_0^2\omega_{p0}^2 r_0^2 exp\left(-\frac{3m\alpha E_0^2}{4Mf^2} + \frac{\xi}{d}\right)}{4c^2 M f^3} - \frac{\xi\omega_{p0}^2 exp\left(\frac{\xi}{d}\right)}{2d\omega^2\left(1 - \frac{\omega_{p0}^2}{\omega^2}exp\left(\frac{\xi}{d}\right)\right)}\left(\frac{df}{d\xi}\right)^2 + \frac{\omega_{p0}^2 exp\left(\frac{\xi}{d}\right)}{2d\omega^2\left(1 - \frac{\omega_{p0}^2}{\omega^2}exp\left(\frac{\xi}{d}\right)\right)}\left(1 - \frac{\xi\omega_{p0}^2 exp\left(\frac{\xi}{d}\right)}{2d\omega^2\left(1 - \frac{\omega_{p0}^2}{\omega^2}exp\left(\frac{\xi}{d}\right)\right)}\right)\frac{df}{d\xi}. \tag{9}$$

RESULTS AND DISCUSSION



(a) Variation of f Vs ξ for uniform density medium

(b) Variation of f Vs ξ for exponential density ramp

(c) Variation of ϕ Vs ξ for uniform density

(d) Variation of ϕ Vs ξ for for exponential density ramp

FIGURE 1: Comparision of f Vs ξ and ϕ Vs ξ for uniform density and exponential density ramp

Equation 9 represent variation of beam width parameter f with normalized distance of propagation ξ for exponential density ramp profile. This is second order nonlinear differential equation and can be numerically solved by choosing following laser-plasma parameters:
$r_0 = 25 \times 10^{-4}$cm, $\omega = 1.7760 \times 10^{15}$rad/s, $n_0 = 3.9645 \times 10^{17}\ cm^{-3}$. $\alpha E_0^2 = 750, d = 10$.
The first term on the right-hand side of Equation 9 corresponds to the diffraction divergence of the beam and the second term corresponds to the convergence resulting from the nonlinearity and remaining terms appears due to plasma density ramp. It is important to note that in absence of density transition and for q = ∞ (Gaussian laser beam) Equation 9 reduces to

$$\frac{d^2 f}{d\xi^2} == \frac{1}{f^3} - \frac{3m\alpha E_0^2 \omega_{p0}^2 r_0^2 exp\left(-\frac{3m\alpha E_0^2}{4Mf^2}\right)}{4c^2 M f^3}. \tag{10}$$

Equation 10 is identical to a similar equation obtained earlier by Sodha et al.[18] for propagation of Gaussian laser beam in collisionless plasma of uniform density. Figure 1a and 1b shows variation of beam width parameter f with respect to normalized propagation distance ξ for plasma medium of uniform density and exponential density ramp respectively. Defocusing effect is observed for lower values of q (=0.5 and 1.0), further increase in value of q results oscillatory self-focusing effect. Strength of self-focusing increases with increase in value of q. It is to be noted that enhanced self-focusing is observed for exponential density ramp profile than uniform density for q> 1. Figure 1c and 1d explain reason of such behavior. In these figures intensity dependent dielectric constant ϕ is plotted as function of normalized propagation distance ξ. In presence of ramp, the value of ϕ increases rapidly as compared to value of ϕ in absence of ramp. Since the strength of self-focusing depends upon the value of ϕ, laser spot size decreases rapidly and become more focused as laser beam goes more deeper into the plasma. From Figure 1b and 1d, it is clear that, f minimum value of f matches with the peak value of ϕ and vice versa for every value of q, along the beam axis. From figures it is clear that exponential upward density ramp profile slowly increases the self-focusing by slowly increasing the density. As the laser propagates through the exponential density ramp region, it sees a slowly narrowing channel. In this plasma environment, the oscillation amplitude of the laser spot size reduces significantly, while its frequency increases. Thus exponential plasma density ramp causes the laser beam to become more focused over several Rayleigh length.

CONCLUSION

In conclusion, we comparatively studied the self-focusing in uniform density and exponential density ramp in collisionless plasma by using usual parabolic equation approach. Following important conclusions are drawn from present analysis:

- Self-focusing power of q-Gaussian laser beam increases with increase in value of q and become maximum for q$\rightarrow \infty$ (i.e. for Gaussian laser beam).
- Enhanced self-focusing is observed for exponential density ramp profile as compare to uniform density for same values of q.

The present results are of relevance in various laser plasma-applications, where propagation of laser beam with localized energy over several Rayleigh length are required.

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