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Dynamics of Gaussian spikes on Gaussian laser beam in relativistic plasma

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Abstract

In the present paper, we have investigated the growth of a Gaussian perturbation superimposed on a Gaussian laser beam. The nonlinearity we have considered is of relativistic type. We have setup the nonlinear differential equations for beam width parameter of the main beam, growth and width of the laser spike by using the WKB and paraxial ray approximation. These are coupled ordinary differential equations and therefore these are simultaneously solved numerically using the Runge Kutta method. It has been observed from the analysis that self-focusing/defocusing of the main beam and the spike determine the growth dynamic of the spike.

Keywords: Gaussian; Growth; Relativistic; Ripple; Self-focusing

1. INTRODUCTION

The most important problem in the laser driven fusion is the efficient coupling of the laser beam with the plasma, so that the plasma can be heated to high temperature. In the experimental situation, where an intense laser beam, traveling through nonlinear self-focusing media, results in multiple filament formation, there is a one-to-one correspondence between filaments and intensity spikes riding with incident laser beam (Abbi & Mahr, 1971). The plasma is one of such nonlinear media. Model used to study the growth dynamics of intensity spikes was proposed as ripple model by Sodha *et al.* (1976) and later on developed to study laser plasma related physics by a number of researchers (Singh & Singh, 1991*a*, 1991*b*; Gill & Saini, 2007; Purohit *et al.*, 2008). Filamentation of the electromagnetic beam in the plasma has been investigated theoretically as well as experimentally in considerable details (Drake *et al.*, 1974; Bingham & Lashmore-Davies, 1976, 1979, 1984; Herbst *et al.*, 1980, 1981; Joshi *et al.*, 1982; ZhiZan *et al.*, 1983; Willi *et al.*, 1984; Young *et al.*, 1988; Rankin *et al.*, 1989). The origin of filamentation instabilities may be due to small scale density perturbation or small scale intensity spike associated with the main beam. The physics of the perturbation, growing at the cost of the main beam is relevant to the inertially confined fusion plasmas. Direct or indirect evidence concentrate on the intensity of the filaments just after its threshold is crossed, and do not go into intermediate details of its growth dynamics. The whole beam self-focusing of laser beam may arise on account of a variety of nonlinearities e.g., from ponderomotive force, collisional non-uniform heating, relativistic effects, etc. Several nonlinear processes occur due to self-focusing effects as observed in a number of recent experiments (Torrisi *et al.*, 2008; Faenov *et al.*, 2007). Further dynamics of ponderomotive channeling in underdense plasma has recently been reported in the experimental observation of large amplitude electric and magnetic fields (Borghesi *et al.*, 2007). In theoretical work on the laser-plasma interaction, it is yet to be understood how the development of the intensity in filaments control its growth dynamics. When a high power laser beam is involved, then it can cause an electron oscillatory velocity comparable to the velocity of light, which modifies the effective dielectric constant of the plasma, and hence affects the self-focusing of the beam. The self-focusing is due to the relativistic mass increase of plasma electrons. Relativistic laser-plasma interaction has been studied in detail by many authors, both theoretically (Kruer, 2000; Osman *et al.*, 1999) and experimentally (Tanaka *et al.*, 2000; Fuchs *et al.*, 1999; Monot *et al.*, 1995), and reviewed thoroughly (Umstadter, 2003; Gibbon & Forster, 1996). Nonlinear processes, playing key role in the generation of new ion sources has been recently reported (Laska *et al.*, 2007;

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Torrisi *et al.*, 2008; Strangio *et al.*, 2007). Further, the importance and relevance of laser produced plasma have opened new vistas in rich field of experiments to study novel physics issues in nuclear and particle physics, atomic physics (Stoehlker *et al.*, 2003), plasma physics (Hoffman *et al.*, 2005; Schaumann *et al.*, 2005), and applied sciences (Kuehl *et al.*, 2007; Kasperczuk *et al.*, 2008).

A laser beam propagating in underdense plasma with a frequency ω_p smaller than the laser frequency ω undergoes relativistic self-focusing as soon as its total power P exceeds the critical value $P_{cr} \sim 17(\omega/\omega_p)^2$ GW, this has been established both theoretically (Max *et al.*, 1974; Hora, 1975; Schmidt & Horton, 1985; Borisov *et al.*, 1992*a*), and experimentally (Borisov *et al.*, 1992*b*; Monot *et al.*, 1995).

The study of the interaction of intense laser pulses with plasmas is relevant for a number of applications such as plasma based accelerators (Modena *et al.*, 1995; Esarey *et al.*, 1996; Umstadter *et al.*, 1996) and the fast ignitor schemes (Tabak *et al.*, 1994) for inertial confinement fusion. Pukhov and Meyer-ter-Vehn (1996) reported three-dimensional particle in cell (3D PIC) simulations for laser pulse propagation in near critical underdense plasmas far above the threshold for relativistic filamentation. The key feature predicted by these simulations is the formation of the narrow, single propagation channel, containing the significant part of the laser energy. The simulation reveals the importance of relativistic electrons traveling with the light pulse and generating multi-mega Gauss magnetic fields that strongly influence the light propagation.

In the present work, we have investigated the growth of the Gaussian ripple superimposed on Gaussian laser beam by taking into account the relativistic nonlinearity. In Section 2, we have setup and solved the wave equation for the main beam. In section 3, we have solved the nonlinearly coupled ordinary differential equations for the growth parameter, and the beam width of the spike. Finally a detailed discussion of the results is presented in Section 4.

2. PROPAGATION OF GAUSSIAN LASER BEAM

Consider the propagation of an electromagnetic wave of angular frequency ω_o in a homogeneous plasma along the z-axis. The initial intensity distribution of the main beam is assumed to be Gaussian and is given by

$$E_o \cdot E_o^\star|_{z=0} = E_{oo}^2 \exp\left[-r^2/r_o^2\right], \tag{1}$$

where $r^2 = x^2 + y^2$ and r_o is the initial width of the main beam.

The electric vector E_o of the main beam satisfies the wave equation

$$\nabla^2 E_o - \nabla(\nabla \cdot E_o) + \frac{\omega_o^2 \epsilon E_o}{c^2} = 0, \tag{2}$$

$$\epsilon = \epsilon_o + \Phi(E_o \cdot E_o^\star) \tag{3}$$

where ϵ_o and $\Phi\,(E_o \cdot E_o^\star)$ are the linear and nonlinear parts of the dielectric constant, respectively and

$$\epsilon_o = 1 - \frac{\omega_p^2}{\omega_o^2}. \tag{4}$$

Here, ω_p is the plasma frequency, given by $\omega_p^2 = 4\pi n_e\, e^2/m_o$ where e_o and m_o are the charge and rest mass of the electron, respectively, and n_e is the density of the plasma electrons. The relativistic general expression for the plasma frequency is given by

$$\omega_{pe}^2 = \frac{\omega_p^2}{\gamma}, \tag{5}$$

where γ is the relativistic factor given by

$$\gamma = [1 + \alpha E_o . E_o^\star]^{1/2}, \tag{6}$$

where $\alpha = e^2/m_o^2 c^2 \omega_o^2$. We can express the nonlinear part of the dielectric constant by the following equation

$$\Phi(E_o \cdot E_o^\star) = \frac{\omega_p^2}{\omega_o^2}\left[1 - (1 + \alpha E_o \cdot E_o^\star)^{-1/2}\right] \tag{7}$$

In Wentzel-Kramers-Brillouin (WKB) approximation, the second term of Eq. (2) can be neglected and the electric vectors of the main beam (E_o) satisfy the following equation

$$\nabla^2 E_o + \frac{\omega_o^2 \epsilon (E_o E_o^\star) E_o}{c^2} = 0. \tag{8}$$

It should be mentioned that the neglection of the term $\nabla\,(\nabla \cdot E_o)$ in Eq. (2) is justified when $(c^2/\omega_o^2)\left|(1/\epsilon)\nabla^2 ln\epsilon\right| << 1$. Now, $E_o = A(r, z)\exp\left[-\iota k_o z\right]$ is introduced, where $A(r,z)$ is a complex function of its argument. The behavior of the complex amplitude $A(r, z)$ is described by the parabolic equation obtained from the wave Eq. (8) in the WKB approximation assuming that the variations in the z -direction are slower than those in the radial direction

$$-2\iota k_o \frac{\partial A}{\partial z} + \nabla_\perp^2 A + \frac{\omega_o^2 \Phi(E_o \cdot E_o^\star) A}{c^2} = 0. \tag{9}$$

In the absence of any spike, one can write

$$A = A_o(r, z)\exp\left[-\iota k_o S_o\right], \tag{10}$$

where $A_o\,(r, z)$ and S_o are real functions of r and z (S_o being the ekional). Substituting Eq. (10) for A in Eq. (9) and separating the real and imaginary parts, one can obtain

$$\begin{aligned} 2\left(\frac{\partial S_o}{\partial z}\right) + \left(\frac{\partial S_o}{\partial r}\right)^2 &= \frac{1}{k_o^2 A_o}\nabla_\perp^2 A_o \\ &+ \frac{\omega_p^2}{\omega_o^2 \epsilon_o}\left[1 - (1 + \alpha E_o \cdot E_o^\star)^{-1/2}\right], \end{aligned} \tag{11}$$

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and

$$\frac{\partial A_o^2}{\partial z} + \left(\frac{\partial S_o}{\partial r}\right)\frac{\partial A_o^2}{\partial r} + A_o^2 \nabla_\perp^2 S_o = 0, \tag{12}$$

Following Akhmanov *et al.* (1968) and Sodha *et al.* (1976), the solution for E_o can be written as

$$\begin{aligned} E_o &= A_o \exp[-\iota k_o(S_o + z)], \\ A_o^2 &= \frac{E_{oo}^2}{f_o^2}\exp\left[-\frac{r^2}{r_o^2 f_o^2}\right], \\ S_o &= \frac{r^2}{2}\beta(z) + \Phi_o(z), \end{aligned} \tag{13}$$

where $\beta_o(z) = (1/f_o)(df_o/dz)$ and $k_o = \omega_o \epsilon_o^{1/2}/c$. The parameter β_o^{-1} may be interpreted as the radius of the curvature of the main beam. f_o is the dimensionless beam width parameter described by the differential equation

$$\frac{d^2 f_o}{dz^2} = \frac{c^2}{\omega_o^2 \epsilon_o r_o^4 f_o^3} - \frac{\alpha E_o^2}{2\epsilon_o r_o^2 f_o^3}\left(\frac{\omega_p^2}{\omega_o^2}\right)\left(1 + \frac{\alpha E_o^2}{f_o^2}\right)^{-(3/2)}. \tag{14}$$

Eq. (14) can be solved numerically with appropriate boundary conditions. One can take $f_o = 1$ and $df_o/dz = 0$, corresponding to an initial plane wave front.

3. TREATMENT FOR THE GAUSSIAN PERTURBATION

Now, we obtain a solution of the quasioptic Eq. (9) for the situation when a single profile of Gaussian spike propagates co-axially with the main laser beam. To obtain a perturbation treatment for the laser spike, we write the optical electric field amplitude in the form

$$A = (A_o + E_1 + \iota E_2)\exp(-\iota k_o S_o), \tag{15}$$

where $E = E_1 + \iota E_2$ is the complex electric field of the perturbation with $E_1, E_2 \ll A_o$, A_o being the unperturbed amplitude of the main laser beam. Substituting Eq. (15) in Eq. (9), one can obtain the following two coupled equations for E_1 and E_2

$$\begin{aligned} &\frac{E_1}{A_o}\nabla_\perp^2 A_o - 2k_o\frac{\partial E_2}{\partial z} = \nabla_\perp^2 E_1 + k_o E_2 \nabla_\perp^2 S_o + 2k_o \frac{\partial E_2}{\partial r}\frac{\partial S_o}{\partial r} \\ &\quad + 2\alpha A_o^2 \frac{\omega_{po}^2}{\omega_o^2}\left(1 + \frac{\alpha E_o^2}{f_o^2}\right)^{-(3/2)}, \end{aligned} \tag{16}$$

and

$$\frac{E_2}{A_o}\nabla_\perp^2 A_o + 2k_o\frac{\partial E_1}{\partial z} = \nabla_\perp^2 E_2 - k_o E_1 \nabla_\perp^2 S_o - 2k_o\frac{\partial E_1}{\partial r}\frac{\partial S_o}{\partial r}. \tag{17}$$

Now we take the form of A_o and S_o as given by Eq. (13), and E_1 and E_2 as

$$E_{1,2} = E_{10,20}\exp[\alpha(z)]\exp\left[-\frac{r^2}{2b^2(z)}\right]. \tag{18}$$

This equation defines the growth parameter $\alpha(z)$, and $b(z)$ is the size of the Gaussian perturbation inside the plasma. The substitution of the Eqs. (13) and (18) in Eqs. (16) and (17) gives the following relations for $\alpha(z)$ and $b(z)$:

$$\begin{aligned} \frac{\partial \alpha}{\partial z} = \frac{1}{k_o}&\left[\left(\frac{1}{b^2} - \frac{1}{r_o^2 f_o^2}\right)\frac{\omega_p^2}{\omega_o^2}\frac{\alpha E_o^2}{f_o^2}\left(1 + \frac{\alpha E_o^2}{f_o^2}\right)^{-(3/2)}\right. \\ &\left. - \left(\frac{1}{b^2} - \frac{1}{r_o^2 f_o^2}\right)\right]^{1/2} - \beta(z), \end{aligned} \tag{19}$$

and

$$\begin{aligned} \frac{\partial b}{\partial z} = \frac{b^3}{2k_o}&\left[\left[\left(\frac{1}{b^4} - \frac{1}{r_o^4 f_o^4}\right)\left\{-3\frac{(\alpha E_o^2)^2}{r_o^2 f_o^6}\frac{\omega_p^2}{\omega_o^2}\left(1 + \frac{\alpha E_o^2}{f_o^2}\right)^{-(5/2)}\right.\right.\right. \\ &\left.\left.\left. - \left(\frac{1}{b^4} - \frac{1}{r_o^4 f_o^4}\right)\right\}\right]^{(1/2)} + \frac{2k_o\beta}{b^2}\right]. \end{aligned} \tag{20}$$

One can solve the differential equations for the initial conditions $b(z=0) = b_o$ and $\alpha(z=0) = 0$.

4. DISCUSSION

Eqs. (14), (19), and (20) are coupled equations. We have solved these equations numerically for the following set of parameters.

$$\left(\frac{r_o\omega_p}{c}\right)^2 = 18.0, \quad \frac{\omega_p}{\omega_o} = 0.03,$$

$\omega_o = 1.778 \times 10^{14}$ rad s^{-1}, $b_o = 4.0 \times 10^{-4}$ cm and for different values of αE_o^2. The results are depicted in the form of graphs in Figures 1 to 6.

Eq. (14) is a nonlinear ordinary differential equation governing the behavior of dimensionless beam width parameter f as a function of distance of propagation. The first term on the right-hand-side of this equation represents the diffraction of the main laser beam and arises due to the second term $\nabla_\perp^2 A$ of Eq. (9). When high intense power laser beam is used, the second term in Eq. (14) arises due to the relativistic nonlinear effect resulting from the relativistic mass correction and depends on intensity factor αE_o^2, relative plasma density ω_p^2/ω_0^2 etc. The diffraction term leads to diffractional divergence of the main beam, while nonlinear term is responsible for self-focusing of beam due to the relativistic effect. The fate of the laser beam *viz* self-focusing/defocusing is ultimately determined by the relative magnitude of these terms. If the first term on right-hand-side of (14) dominates

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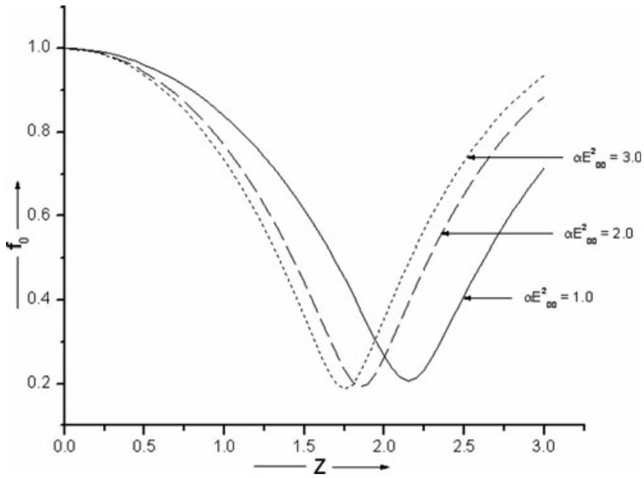

Fig. 1. Beam width parameter f_0 plotted against the distance of propagation Z in relativistic Plasma for intensities $\alpha E_{00}^2 = 1.0, 2.0, 3.0$ and for the following set of parameters.

$$\left(\frac{\omega_p r_0}{c}\right)^2 = 18.0,\ \frac{\omega_p}{\omega_0} = 0.03,\ \omega_0 = 1.778 \times 10^{14} rads^{-1}$$

$$b_0 = 4 \times 10^{-4}\, cm.$$

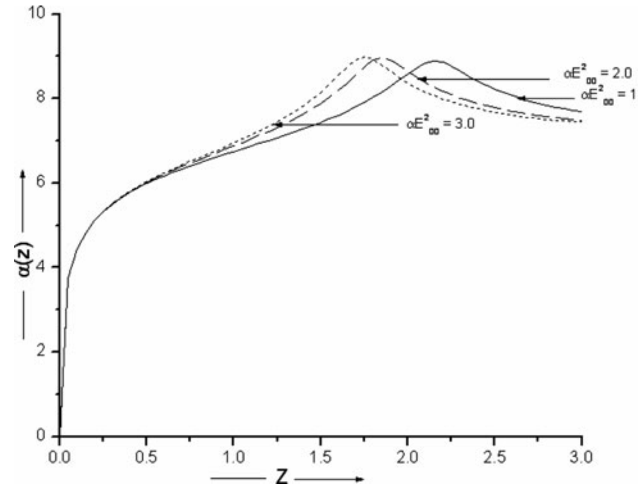

Fig. 3. Growth $\alpha(z)$ of the spike plotted against the distance of propagation Z in relativistic Plasma for intensities $\alpha E_{00}^2 = 1.0, 2.0, 3.0$ and for the parameters mentioned in Figure 1.

over the second term, the beam diverges, while opposite is true when the second term exceeds the first one. Eqs (19) and (20) are nonlinear ordinary differential equations and are coupled to each other as well as to the main laser beam. Eqs. (19) and (20) govern the evolution of growth rate and beam width of the spike respectively.

Figures 1, 2, 3 present the variation of the beam width parameter f_o of the main beam, the beam width $b(z)$ and the growth $\alpha(z)$ of the spike, respectively, with the distance of propagation for three values of intensity $\alpha E_o^2 = 1.0, 2.0, 3.0$.

It is observed from Figure 1 that diffraction of the main beam starts earlier if the value of the intensity parameter is increased. This is due to the dominance of the diffractive term over the nonlinear self-focusing term with the increase in intensity. It is clear from the Eq. (14) that, if we increase the intensity, the term $\left(1 + (\alpha E_o^2/f_o^2)\right)^{-3/2}$ will further weaken the nonlinear term in comparison with the diffractive term, and hence, the diffraction starts earlier at higher intensity. It is further observed from the graph that the distance of propagation of the beam, before it gets self-focussed, decreases with increase in the intensity of the main beam. This is due to the fact that at relativistic intensity, the quasi-stationary magnetic field is generated. So, if we increase the intensity of the main beam, a stronger magnetic field is generated, the pinching effect of which adds to the self-focusing (Pukhov & Meyer-ter-Vehn, 1996).

It is observed from Figure 2 that there exists a defocusing of the spike width for the initial distance of propagation. This is due to the dominance of the diffraction divergence over the refractive term for the initial distance of propagation,

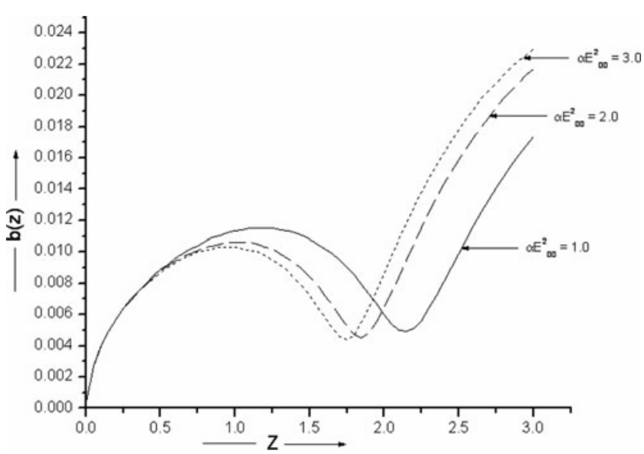

Fig. 2. Spike width $b(z)$ plotted against the distance of propagation Z in relativistic Plasma for intensities $\alpha E_{00}^2 = 1.0, 2.0, 3.0$ and for the parameters mentioned in Figure 1.

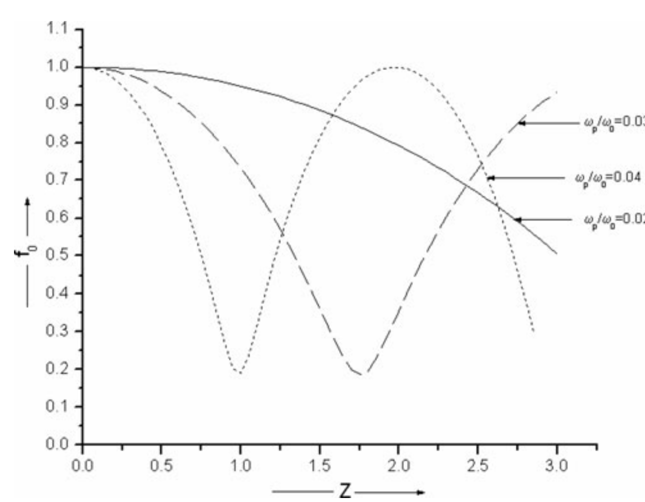

Fig. 4. Beam width parameter f_0 plotted against the distance of propagation Z in relativistic Plasma for $\omega_p/\omega_0 = 0.02, 0.03, 0.04$, $\alpha E_{00}^2 = 3.0$ and for the parameters mentioned in Figure 1.

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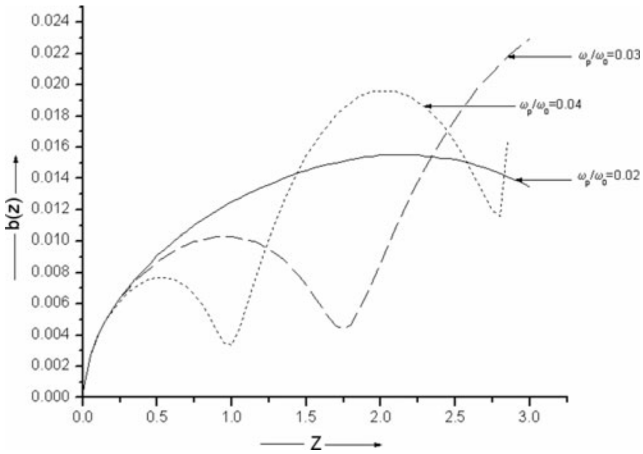

Fig. 5. Spike width $b(z)$ plotted against the distance of propagation Z in relativistic Plasma for $\omega_p/\omega_0 = 0.02, 0.03, 0.04$, $\alpha E_{00}^2 = 3.0$ and for the parameters mentioned in Figure 1.

however, with the further increase in distance of propagation, there occurs a relative shift of focii with intensity, *viz.* the focusing length decreases proportionally to the increase in intensity. This is vividly shown in Figure 2. It is further observed that after the initial distance of propagation, the spike width shows a similar behavior as the main beam. So it is concluded that there is strong coupling between the main beam and the spike of the beam after the initial distance of propagation.

It is found from Figure 3 that the growth $\alpha(z)$ reaches its maximum value and then decreases slowly. The maxima corresponding to $\alpha E_o^2 = 1.0, 2.0, 3.0$, obviously correspond to the minima of the main beam and the spike, and thereafter the growth gets stabilized. Thus, the stabilization of the growth is clearly linked with the defocusing of the main beam and the spike width $b(z)$.

Figures 4, 5, and 6 depict the variation of beam width parameter f_o of the main beam, beam width $b(z)$ and growth $\alpha(z)$ of the spike, respectively, with distance of propagation for three values of plasma density, $\omega_p/\omega_o = 0.02$, 0.03, and 0.04, respectively at $\alpha E_{oo}^2 = 3.0$.

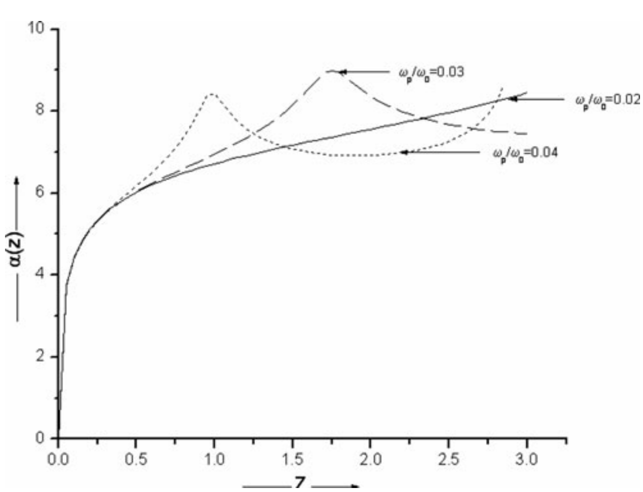

Fig. 6. Growth $\alpha(z)$ of the Spike plotted against the distance of propagation Z in relativistic Plasma for $\omega_p/\omega_o = 0.02, 0.03, 0.04$, $\alpha E_{oo}^2 = 3.0$ and for the parameters mentioned in Figure 1.

It is observed from Figure 4 that focusing of the beam takes place earlier if we increase the plasma density. This is due to the fact that, at relativistic intensities, if we increase the plasma density a beam with more relativistic electrons travels with the laser pulse, which generates a higher current, and ultimately a very high quasi-stationary magnetic field is generated. Therefore, the pinching effect of the magnetic field becomes stronger, which further adds to self-focusing. This prediction is in agreement with the simulation (3D PIC) results reported by Pukhov and Meyer-ter-Vehn (1996). The results observed from graph 5 and 6 for width $b(z)$ and growth $\alpha(z)$ of the spike are similar to that obtained from Figure 2 and Figure 3.

5. CONCLUSIONS

In this research work, we have studied the growth of the Gaussian ripple superimposed on Gaussian laser beam by taking into account the relativistic nonlinearity. The results obtained have several ramifications as follows: (1) Our results confirm the role of relativistic electrons traveling with the light pulse, reported by Pukhov and Meyer-ter-Vehn (1996) in their (3D PIC) simulation study. (2) Strong coupling between the main beam and the spike of the beam is observed. (3) Defocusing of the main beam and the spike leads to stabilization of the growth rate of the spike. The results of the present analysis are useful in understanding physics issues of the high power laser driven fusion, as well as the coupling physics involved in laser-plasma interactions.

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