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Nonlinear Structure of the Underdense Collisional Plasma Driven by High Intensity Short Laser Pulse with Linear Polarization: Enhanced Propagation and Focusing

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ABSTRACT: In the current theoretical study, by considering that the electric and magnetic fields of the laser pulse are perpendicular to external guide magnetic field and with assumption an azimuthally polarized laser pulse we have studied the nonlinear structure of laser pulse propagation of an ultra-short laser beam in underdense collisional magnetized plasma. An external magnetic field is applied in the direction of laser beam propagation in homogeneous plasma. To achieve the nonlinear equation for the electric field in the plasma, we use the Maxwell equations and the equation of electrons motion while taking into account the average ponderomotive force per unit volume acting on the plasma electrons. We show that in the presence of external magnetic field in the direction of laser beam propagation, the density of the electrons increases. From the results, in magnetized plasma, field wavelength is increased relative to the wavelength in unmagnetized plasma in the similar conditions. By adjusting the magnitude of the external magnetic field, initial electrons speed, and laser intensity, the desired value of the electron density can be produced.

KEYWORDS: laser-plasma interaction, magnetic fields, electric fields, plasma density, dielectric permittivity.

I. INTRODUCTION

Very intense laser pulses, approaching the relativistic intensity regime are already, or will be soon available in many laser laboratories and infrastructures.More than a half century ago, it was shown that the electromagnetic field can exert a force on the charged particles through the mean square electric field [1].The research of the femtosecond laser-plasma interactionis of importance because of many potential applications. In spite of such extensive work over the years, the understanding of the physics of the laser-plasma interaction is still an active part of research, which finds wide application in the areas like plasma based focused ion beams [2-3],plasma sources for negative ion beams for neutral beam injection [4], material processing [5], heating of fusion plasmas [6],rf based plasma thrusters [7], etc [8-11].

Several nonlinear phenomena will appear in the laser-plasma interaction region. One of them is self-focusing and defocusing of high intensity laser beam propagating through plasma [12-13]. Gaussian profile of the intense laser beam leads to modifying the plasma refractive index which may lead to self-focusing or defocusing of the laser beam in the propagation path. Any external force can affect density and velocity of the electrons in plasma. So, imposing external magnetic field can modify the density profile of the plasma electrons by changing the electrons velocity and generate a new component for electrons velocity vector. Changing in the electrons density and velocity vector modifies dispersion relation of the laser beam and nonlinear current density of the plasma electrons. Therefore, imposing external magnetic field can modify self-focusing property of the laser beam propagating in plasma. The direction of the external magnetic field vector is an important parameter in the influence of the external magnetic field on self-focusing property. Changing in direction of the external magnetic field can change contribution of the electrons velocity components therefore modifies electrons current density.

The interaction between intense laser radiation and matter is known to produce a wealth of nonlinear effects. Those include fast electron and ion generation indicating that ultra-strong electric fields are produced in the course of the

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laser-plasma interaction. An equally ubiquitous, although less studied, effect accompanying laser-plasma interaction is the generation of ultra-strong magnetic field in the plasma. Magnetic field can have a significant effect on the overall propagation and plasma dynamics [14]. Extremely high (few mega gauss) magnetic field play an essential role in the particle transport, propagation of laser pulses, laser beam self-focusing, penetration of laser radiation into the overdense plasma and the plasma electron and ion acceleration [15].It is established theoretically and experimentally that magnetic field spontaneously arises in the laser-produced plasmas and the magnitude of the experimentally observed self-generated magnetic field [16-17] is up to a few hundred Mega-Gauss [18]. This self-generated magnetic field can affect the propagation and focusing of laser beam in plasmas [19].
To illustrate the relativistic interaction regime, we consider a free electron in a plane electromagnetic wave propagating, say, in the z direction, with electric field in the x-direction and magnetic field in y-direction. In the low intensity regime, one can apply the linear response theory for which the electron oscillates along the direction of the electric field. In the relativistic regime, the magnetic field curves the electron trajectory towards the z-direction. In the present paper, we describe the propagation of an intense, linearly polarized Gaussian electromagnetic beam in collisional magnetized plasma. The magnetic field can be self-generated or externally applied during laser-plasma interaction. The relativistic oscillation of the mass of the electron in the field of the pump and longitudinal magnetic field are shown to have a major effect on the dynamics of the propagation of intense laser pulse. Analytical formulation of the propagation characteristics of the Gaussian laser beams in collisional isothermal magnetized plasma by taking into account the nonlinear effects of the ponderomotive force in presence of the external magnetic fieldis presented in Section II. Here, presenting the effect of the external magnetic field strength on the self-focusing of the laser beam in a nonrelativistic regime, we will show that for a suitable choice of the pulse intensity and external magnetic field strength, self-focusing has the strongest effect. Section III is devoted to the results and discussion and Sec. IV includes conclusion.

I. THE THEORETICAL MODEL AND FORMULATION

The specific configuration we consider is a semi-infinite plasma ($z > 0$) in a constant external magnetic field, $\mathbf{B}_0$ ($= \mathrm{B}_0 \hat{e}_z$), and a linearly polarized electromagnetic wave, i.e., a laser pulse characterized in terms of amplitude, wave number, and frequency, E, k, and ω as,

$$\mathbf{E} = \mathrm{E}\, e^{i(kz-\omega t)}\, \hat{e}_x, \tag{1}$$

$$\mathbf{B} = \frac{k}{\omega} \mathrm{E}\, e^{i(kz-\omega t)}\, \hat{e}_y. \tag{2}$$

The $z > 0$ region is taken to be filled with a homogeneous density profile of plasma with a plasma-vacuum interface at z=0.The electromagnetic wave enters normally into the plasma slab.To develop the wave equation for the oscillating electric and magnetic fields, one can start with Faraday's induction and Ampere's laws. By considering these Maxwell's equations, we have

$$\nabla \times \mathbf{E} = i\omega \mathbf{B}, \tag{3}$$

$$\nabla \times \mathbf{B} = \mu_0 (\mathbf{J} - i\varepsilon_0 \omega \mathbf{E}). \tag{4}$$

Taking the curl of Eq. (3) and substituting from Eq. (4), we obtain the wave electric field equation as follows [20, 21]:

$$\nabla^2 \vec{\mathbf{E}} - \nabla(\nabla.\vec{\mathbf{E}}) + i\omega\mu_0 \vec{\mathbf{J}} = 0. \tag{5}$$

Now, to obtain the laser pulse electric field in plasma, we should use the appropriate electron current density $\vec{J}$ in Eq. (5). Using the equation of electrons motion, taking into account a ponderomotive force due to the high-frequency laser field and considering a collisional isothermal plasma, we have

$$m_e n_e \frac{d\mathbf{V_e}}{dt} = -e n_e [\mathbf{E} + (\mathbf{V_e} \times \mathbf{B})] - m_e n_e \upsilon_{ei} \mathbf{V_e} - \nabla P_e + \mathbf{F_{Pe}}, \tag{6}$$

where n_e, V_e, m_e, $P_e (= n_e T_e)$, and F_{Pe} are the density, velocity, mass, pressure of electrons, and the average ponderomotive force per unit volume acting on the plasma electrons, respectively. In this work, since the ion mass is

much greater than the electron mass, and $\omega \gg \omega_{pi}$, we neglect ion motions. Then, by writing Eq. (6) in $\hat{e}_x$ and $\hat{e}_y$ directions, and substituting Eqs. (1) and (2), the scalar equations of motion may be written in the form of

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$$\frac{dv_x}{dt} = -\omega_l\left(1-\frac{v_z}{v_p}\right) - \omega_0 v_y - \upsilon_{ei} v_x, \tag{7}$$

$$\frac{dv_y}{dt} = \omega_0 v_x - \upsilon_{ei} v_y. \tag{8}$$

In the above equations, $\omega_0 = eB_0/m_e$ and $\omega_l = eE_x/m_e$ are the electronscyclotron frequency due to the existence of the externalmagnetic field and laser pulse electric field, respectively. υ_{ei} is the collisional frequency between thecharged particles (electrons and ions) and v_p denotes the phase velocity for the laser pulse.The analytical solutions of Eqs. (7) and (8) for the transverse electron velocity components of magnetized collisional plasma in presence of axial guide magnetic fields can be obtained as

$$v_x = \frac{ie}{m_e\widehat{\omega}}\frac{1-\frac{v_z}{v_p}}{1-(\frac{\omega_0}{\widehat{\omega}})^2}E_x, \tag{9}$$

$$v_y = \frac{e}{m_e\widehat{\omega}}\left(\frac{\omega_0}{\widehat{\omega}}\right)\frac{1-\frac{v_z}{v_p}}{1-(\frac{\omega_0}{\widehat{\omega}})^2}E_x. \tag{10}$$

Where$\widehat{\omega} = \omega + i\upsilon_{ei}$. Here, the plasma electrons current density is obtained as

$$J_x = -en_e v_x = -\frac{i\varepsilon_0{\omega_p}^2}{\widehat{\omega}}\frac{1-\frac{v_z}{v_p}}{1-(\frac{\omega_0}{\widehat{\omega}})^2}E_x, \tag{11}$$

where ${\omega_p}^2 = n_e e^2/\varepsilon_0 m_e$is the plasma electrons frequency and n_e is the plasma density.

The propagation of a strong electromagnetic wave in an under dense plasma can be accompanied by the ponderomotive (Miller) force. Here the spatial distribution of the electron density and the dielectric permittivity of the plasma change under the action of the ponderomotive force. Consequently, the profiles of the electric and magnetic fields of the electromagnetic wave (microwave) change into the plasma. The ponderomotive force on a single electron is the same as the nonlinear Lorentz force and is proportional to the gradient of the wave intensity. It is expected that a perceptible ponderomotive effect on the plasma density distribution in a high frequency plasma discharge (such as microwave and radio frequency discharges) exists when the ponderomotive force is comparable to, or larger than, the competing plasma pressure gradient force[22-24]. In this situation and when the plasma is considered as fluid, self-generated forces can be neglected. Moreover, at the plasma boundary, where the mode encounters the plasma in the second waveguide, the ponderomotive force would be dominant over the pressure gradient force. Hence, the interaction of the microwave and the plasma in the waveguide can be investigated by neglecting such plasma boundary effects and the microwave field at the plasma boundary can be assumed the same as in the evacuated waveguide. The average ponderomotive force per unit volume acting on the electrons (ions are taken fixed due to their heavy mass) in the plasma is the same as the nonlinear Lorentz force, given by

$$\vec{F}_P = -\frac{n_e e^2}{m_e\omega^2}\vec{\nabla}|E|^2. \tag{12}$$

In the steady state, the ponderomotive force in attendance of the external magnetic field and collisional effects can be balanced with the electron pressure gradient force. Consequently, according to the momentum transfer equation (6) in the laser pulse propagation direction and assuming that the electron temperature T_e is independent of coordinates, we have [24],

$$\frac{n_e e^2}{m_e}\left(\frac{1-\frac{v_z}{v_p}}{\omega^2+\upsilon_{ei}^2-\omega_0^2}\right)\frac{dE_x^2}{dz} = T_e\frac{dn_e}{dz}, \tag{13}$$

where $T_e$is taken to be constant. Integration of Eq. (13) yields the expression for the electron density as

$$n_e(z) = n_{0e}\exp\left[\frac{e^2(1-\frac{v_z}{v_p})E_x^2(z)}{m_e T_e(\omega^2+\upsilon_{ei}^2-\omega_0^2)}\right]. \tag{14}$$

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Therefore, the density shall get modified in accordance with the field E. It should be noted that, in the intermediate intensities ($10^{14} - 10^{16}\mathrm{Wcm^{-2}\mu m^2}$) with laser pulse duration of order a few ns, it is convenient to assume that T_e is constant and the dominant spatial dependence comes from the electron density n_e [25]. This equation shows that the electron density is modified by the ponderomotive force. Furthermore, by substituting Eq. (14) into Eq. (11) and using Eq. (5), the nonlinear equation for electric field propagation in collisional plasma is obtained as

$$\frac{d^2}{dz^2}E_x + \frac{\omega^2}{c^2}\left\{1 + \left(\frac{{\omega_p}^2}{\omega\widehat{\omega}}\frac{1-\frac{v_z}{v_p}}{1-(\frac{\omega_0}{\widehat{\omega}})^2}\right)\times \exp\left(\frac{e^2(1-\frac{v_z}{v_p})E_x^2(z)}{m_e T_e(\omega^2+\upsilon_{ei}^2-\omega_0^2)}\right)\right\}E_x = 0. \quad (15)$$

Here, ${\omega^2}_{p0} = n_{e0}e^2/\varepsilon_0 m_e$ is the plasma electrons frequency with the initial homogeneous background density n_{e0}. In addition, the dielectric constant of magnetized collisional plasma can be found as follows:

$$\varepsilon = 1 + \left\{\left(\frac{1-\frac{v_z}{v_p}}{\omega^2+\upsilon_{ei}^2-\omega_0^2}\right)\left({\omega_p}^2 + \frac{i\upsilon_{ei}{\omega_p}^2}{\omega}\right)\right\}. \quad (16)$$

As we see, it should be noted that the electromagnetic wave equation coupled with the equations of momentum transfer, particle conservation and energy in their stationary form and they are solved for obtaining the dielectric permittivity. Now, with having the dielectric permittivity variations, the electric field propagation through the plasma along the z direction is obtained as Eq. (5). In addition, withhaving the electric field variation according to the Eq. (5), we can reach the quiver velocities of electrons Eqs. (9) and (10) and their variations in plasma. Here, the velocities depend on the electrons density, temperature parameters. In other words, as E_x was obtained from Eq. (5), in which the current density J_x depends on plasma electrons' density and temperature, we can conclude that the theta component of electric field is a function of temperature. Furthermore, as we know, for obtaining the ponderomotive force we should use the nonlinear theory [21]. Here, it should be mentioned that the following equations, i.e., momentum transfer and the laser pulse electric field propagation in plasma have the directional dependence on the nonlinear ponderomotive force, and according to it, we conclude that all of them are nonlinear. Now, we analyze the nonlinear wave equation, dielectric permittivity, and the plasma electron density distribution in such plasmas. Substituting Eq. (14) into Eqs. (15) and (16), results in the inhomogeneous dielectric permittivity and the nonlinear equation for the electric field propagation in collisional isothermal magnetized plasma:

$$\varepsilon = 1 + \left\{\left(\frac{1-\frac{v_Z}{v_p}}{\omega^2+\upsilon_{ei}^2-\omega_0^2}\right)\left({\omega_{p0}}^2 + \frac{i\upsilon_{ei}{\omega_{p0}}^2}{\omega}\right)\right\}\times \exp\left(\frac{e^2(1-\frac{v_Z}{v_p})E_x^2(z)}{m_e T_e(\omega^2+\upsilon_{ei}^2-\omega_0^2)}\right), \quad (17)$$

$$\frac{d^2}{dz^2}E_x + \frac{\omega^2}{c^2}\times \left\{1 + \left(\frac{1-\frac{v_Z}{v_p}}{\omega^2+\upsilon_{ei}^2-\omega_0^2}\right)\left({\omega_{p0}}^2 + \frac{i\upsilon_{ei}{\omega_{p0}}^2}{\omega}\right)\times \exp\left(\frac{e^2(1-\frac{v_Z}{v_p})E_x^2(z)}{m_e T_e(\omega^2+\upsilon_{ei}^2-\omega_0^2)}\right)\right\}E_x = 0. \quad (18)$$

I. RESULTS AND DISCUSSION

In Sec. II, we investigated the theoretical model and formulated the nonlinear ponderomotive force effects on isothermal collisional magnetized underdense plasma. From Eq. (18), it is clear that this equation is intensively nonlinear and does not have any analytical solution. Thus, we use the fourth-order Runge-Kutta method to solve this equation numerically and find the mentioned changes inside plasma. In order to obtain the laser pulse electric field, electron density, spatial damping of a laser pulse energy, and the fraction of absorption coefficient profiles, we introduce some dimensionless variables as follows:

$$a = \frac{eE}{mv_s\omega} \quad , \quad \Omega_0 = \frac{\omega_0}{\omega} \quad , \quad \Omega_p = \frac{\omega_{p0}}{\omega} \quad , \quad \Omega_{ei} = \frac{\upsilon_{ei}}{\omega} \quad , \quad \frac{v_z}{v_p} = v$$

where $v_s = (T_e/m)^{1/2}$ is the sound velocity. Using these dimensionless parameters, Eqs. (14), (15), and (16) are written as follows:

$$\frac{n}{n_0} = \exp\left(\frac{(1-v)a^2}{1+\Omega_{ei}^2-\Omega_0^2}\right), \tag{19}$$

$$\varepsilon = 1 + \left\{\left(\frac{1-v}{1+\Omega_{ei}^2-\Omega_0^2}\right)\left(\Omega_p^2 + i\Omega_{ei}\Omega_p^2\right)\right\} \times \exp\left(\frac{(1-v)a^2}{1+\Omega_{ei}^2-\Omega_0^2}\right), \tag{20}$$

$$\frac{d^2a}{d\xi^2} + \left\{1 + \left(\frac{(1-v)\Omega_p^2}{1+\Omega_{ei}^2-\Omega_0^2}\right)(1+i\Omega_{ei}) \times \exp\left(\frac{(1-v)a^2}{1+\Omega_{ei}^2-\Omega_0^2}\right)\right\} a = 0. \tag{21}$$

Here, in the case of collisional magnetized isothermal plasmas the following parameters of the laser beam and plasma have been chosen: $\Omega_{ei} = 10^{-2}$, $\Omega_p = 0.6$, and $T_{e0} = 1$Kev. We know, in plasma when the condition of $n_e < n_{critical}$ is satisfied the plasma is underdense and in the other case when this condition is not satisfied the plasma is overdense. Here in this work, because of the parameter $n_e/n_{critical}$ is proportional with Ω_p^2 , the range of $n_e/n_{critical}$ is 0.36 and n_e is very small in comparison with $n_{critical}$ and the plasma is underdense.

The curves in Figs. 1(a)–1(c), shows the electric field, the distribution of the electron density, and the effective permittivity of magnetized collisional plasma for different values of v_z/v_p (the ratio of electron velocity in z direction to phase velocity of laser pulse) respectively. One can see that the period of oscillations increases and the amplitude of oscillation decreases by increasing the maximum electron density. It is evident that the departure from a sinusoidal shape is stronger for the electron density variation $\Delta n_e/n_{e0}$ than that for the field. Also, these profiles show that the electron density oscillations become highly peaked in the high fraction of v_z/v_p. It is noticeable that by increasing laser pulse intensity, the period of oscillations of the effective permittivity increases and the amplitude of oscillation decreases. In Figs. 2(a)–2(c), the effect of increasing laser intensity on the propagation of the electric field, the distribution of the electron density, and the effective permittivity of magnetized collisional plasma are shown. In these figures, the normalized external magnetic field is taken as $\Omega_0 = 0.4$. Since laser intensity is proportional to the square of amplitude, the amplitude of the electric field in plasma is increased with increasing laser intensity. Furthermore, due to further decrease in the electron density in higher laser intensities, more decrease in the wavelength of fields takes place. The steepening of the electron density distribution is enhanced with an increase in laser pulse intensity. It is seen that when laser intensity is increased, the oscillations of the electron density become highly peaked and at the same time, their wavelengths tend to decrease. The physical reason of this effect is that since λ (the oscillation wavelength) is proportional to $\varepsilon^{1/2}$, then by increasing the dielectric constant, the wavelength of electron's oscillation is decreased. It is interesting to note that by increasing the laser intensity, one can see that the departure from sinusoidal shape is stronger for the electrons density variations than that for the fields. It is noticeable that by increasing laser pulse intensity, the oscillations of the effective permittivity become highly peaked and the wavelength of these oscillations is decreased. Furthermore, we can see that by increasing laser intensity, the oscillations of the effective permittivity are deviated from sinusoidal shape more intensively. Figures 3(a)–3(c) show the effect of the magnitude increment of the external magnetic field on the profiles of the electric field, the electron density distribution, and the effective permittivity in underdense collisional isothermal magnetized plasma in the situation of constant laser intensity. In the presence of the external magnetic field parallel to the laser pulse propagation direction, the electrons density distribution is increased in comparison to unmagnetized collisional isothermal plasma. In this case the electron density distribution is increased more in comparison with the electron density profile presented in the Ref. [25]. Here, the laser pulse should transfer more energy to the plasma electrons compared to unmagnetized plasma. It leads to an increase in the wavelength of the electric field. It is obvious that by increasing the external magnetic field, as a result of the increase of the electrons density distribution, the dielectric permittivity constant is decreased. This results is similar as obtained by Sedaghat *et al.* [25] but different in theadditionalvariablev_z/v_p.

IV. CONCLUSION AND SUMMARY

In this work, by using the Maxwell and hydrodynamic equations, taking into account the ponderomotive force, the interaction of a high-frequency laser pulse with a underdense magnetized collisional isothermal plasma is investigated.

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From the results, one can see, in magnetized plasma, field wavelength is increased relative to the wavelength in unmagnetized plasma in the similar conditions. In the presence of the external magnetic field, the plasma electrons density is increased and due to this effect, the effective permittivity of mentioned plasma are decreased. Also, we have shown that by increasing the maximum electron density, the field and electron density oscillations become lengthened. Our numerical results are in good agreement with numeric simulation performed. Magnetized plasma plays as a capable medium to convert different inertial energies to tunable coherent radiation. This is because the electron density distribution is proportional to the plasma frequency and the magnitude of the external magnetic field at constant laser intensity. By adjusting the magnitude of the external magnetic field, initial electrons speed, and laser intensity, the desired value of the electron density can be produced.

Fig. 1

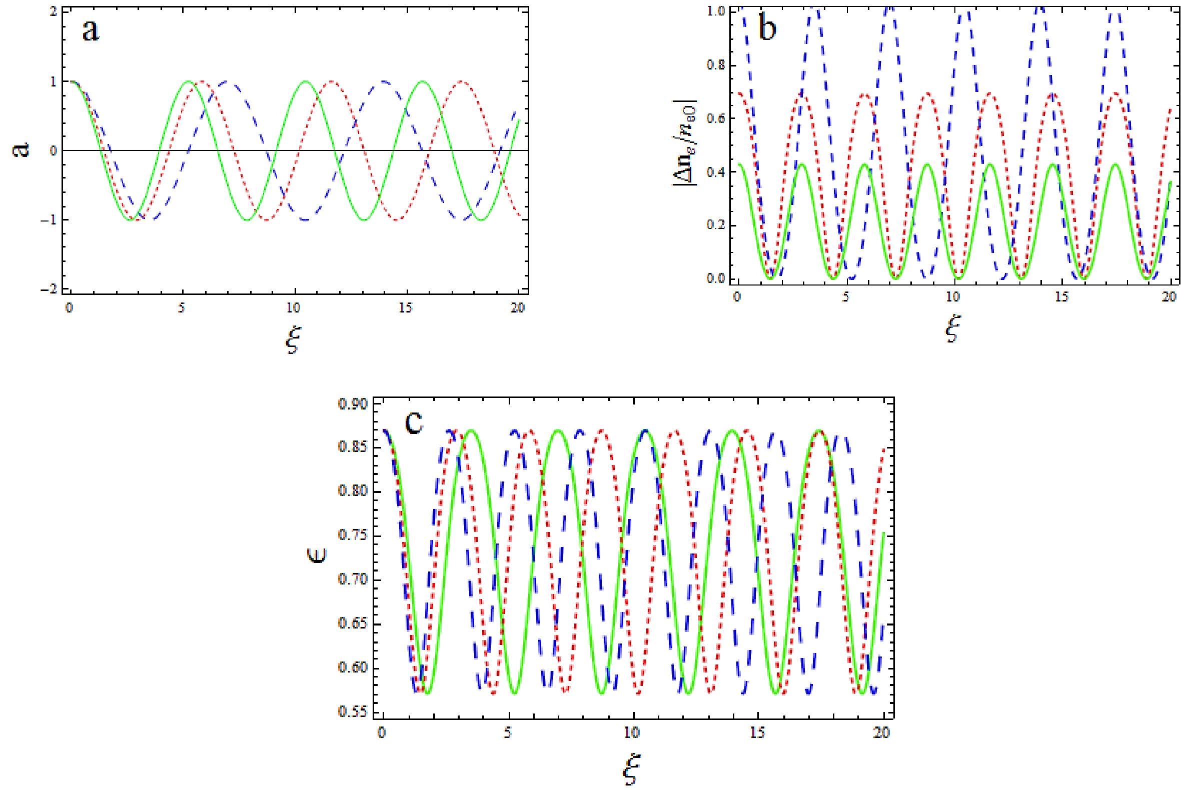


Fig.2

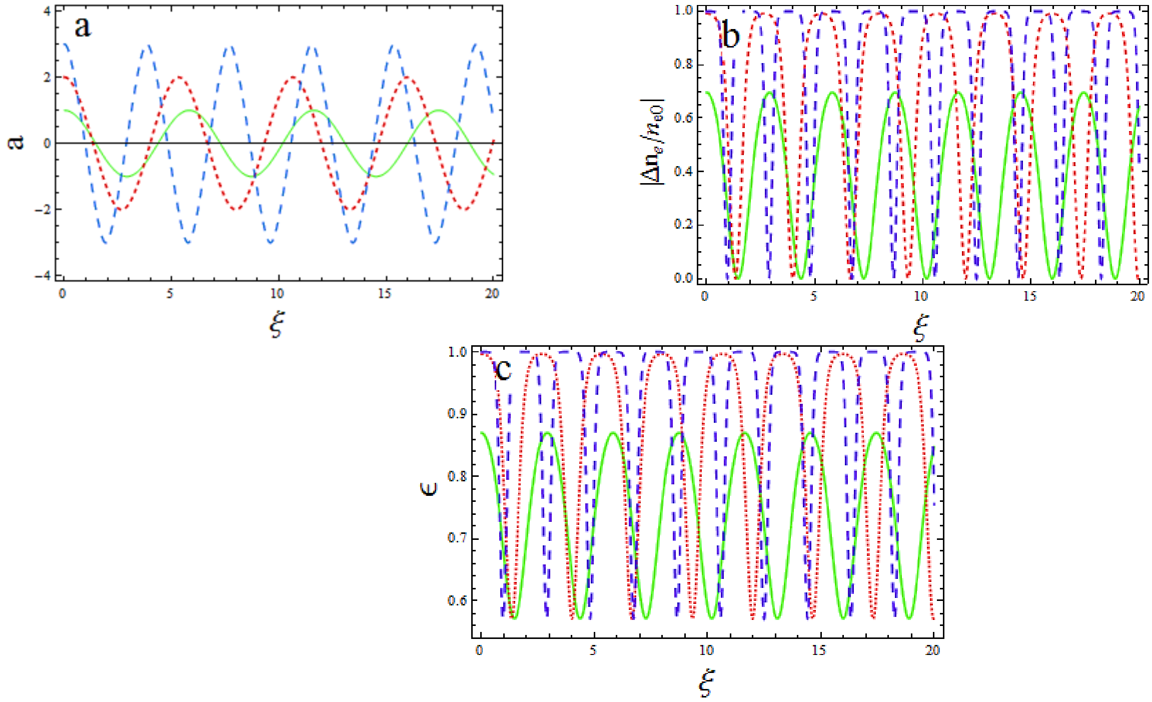
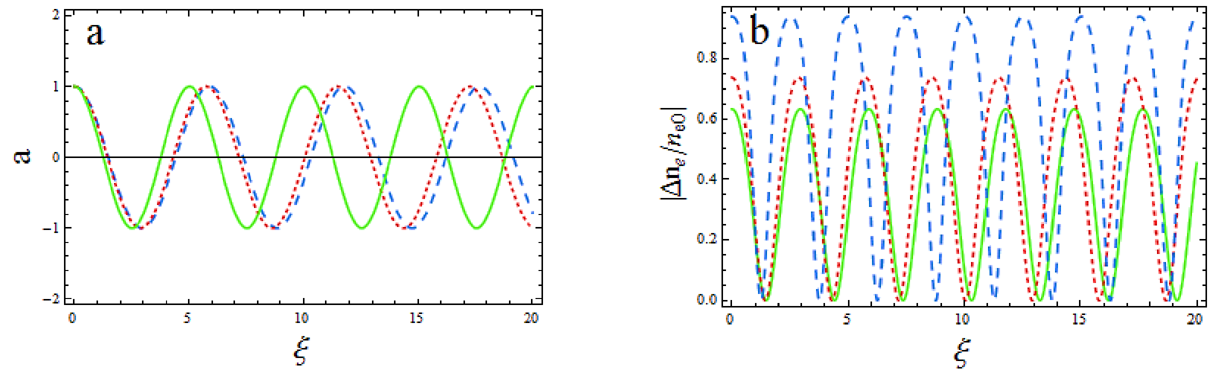


Fig. 3



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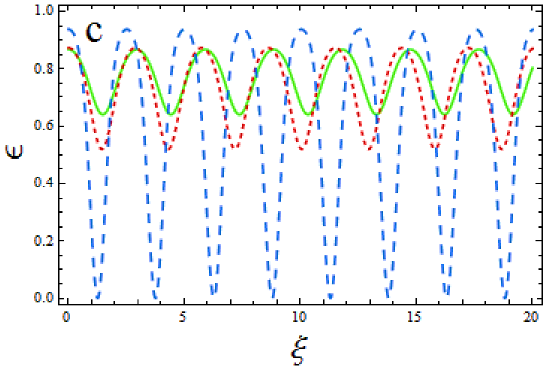

V. FIGURE CAPTIONS

Fig. 1. The effect of increasing theratio of electron velocity in z direction to phase velocity of laser pulse v_z/v_p in the case of the collisional, magnetized, and isothermal plasma on the variations of the (a) normalized electric field, (b) normalized electrons density $\Delta n_e/n_{e0}$, and (c) effective permittivity. Electron temperature is $T_{e0} = 1$Kev, the dimensionless laser pulse intensities is $a_0 = 1$ ($I\lambda^2 = 1.2 \times 10^{15}Wcm^2\mu m^2$), the normalized cyclotron frequency is $\Omega_0 = 0.4$ ($B_0 = 42.8$ MG), the normalized collisional frequency is $\Omega_{ei} = 10^{-2}$, and the normalized plasma frequency is taken as $\Omega_p = 0.6$. The v_z/v_p is equal to zero (solid line), $v_z/v_p = 1.3$ (dotted line), and $v_z/v_p = 1.6$ (dashed line).

Fig. 2. The effect of increasing the laser pulse intensity in the case of the collisional magnetized and isothermal plasma on the variations of the (a) normalized electric field, (b) normalized electrons density $\Delta n_e/n_{e0}$, and (c) effective permittivity. Electron temperature is $T_{e0} = 1$Kev, the ratio of electron velocity in z direction to phase velocity of laser pulse is $v_z/v_p = 1.3$, the normalized cyclotron frequency is $\Omega_0 = 0.4$ ($B_0 = 42.8$ MG), the normalized collisional frequency is $\Omega_{ei} = 10^{-2}$, and the normalized plasma frequency is taken as $\Omega_p = 0.6$. The dimensionless laser pulse intensities are: $a_0 = 1$ (solid line), $a_0 = 2$ (dotted line), and $a_0 = 3$ (dashed line).

Fig. 3. The effect of increasing the external magnetic field in the case of the collisional, magnetized, and isothermal plasma at the dimensionless laser pulse intensity of $a_0 = 1$ on the variations of the (a) normalized electric field, (b) normalized electrons density $\Delta n_e/n_{e0}$, and (c) effective permittivity for different values of normalized cyclotron frequency $\Omega_0 = 0$ (solid line), $\Omega_0 = 0.5$ (dotted line), $\Omega_0 = 0.9$ (dashed line) is shown. Electron temperature is $T_{e0} = 1$Kev, the ratio of electron velocity in z direction to phase velocity of laser pulse is $v_z/v_p = 1.3$, the normalized collisional frequency is $\Omega_{ei} = 10^{-2}$, and the normalized plasma frequency is taken as $\Omega_p = 0.6$.

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