Polarization effect on the relativistic nonlinear dynamics of an intense laser beam propagating in a hot magnetoactive plasma

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Nonlinear dynamics of an intense circularly polarized laser beam interacting with a hot magnetized plasma is investigated. Using a relativistic fluid model, a modified nonlinear Schrödinger equation is derived based on a quasineutral approximation, which is valid for hot plasma. Using a three-dimensional model, spatial-temporal development of the laser pulse is investigated. The occurrence of some nonlinear phenomena such as self-focusing, self-modulation, light trapping, and filamentation of the laser pulse is discussed. Also the effect of polarization and external magnetic field on the nonlinear evolution of these phenomena is studied.

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I. INTRODUCTION

The nonlinear propagation of intense laser pulses in plasma is one of the important recent areas of research with many applications including charged particle acceleration in the plasma wakefield [1–3], laser fusion [4–6], higher harmonics generation [7–11], magnetic field generation [12], x-ray lasers [13–15], etc. When an intense laser pulse propagates through plasma, it can cause several instabilities, by which it may be scattered or absorbed. However, modulation, filamentation, and self-focusing are the well-known phenomena which can amplify the intensity of the laser beam passing through a plasma. Self-focusing is a nonlinear optical phenomenon that appears when the refractive index of the medium exposed to the intense electromagnetic radiation changes [16–18]. When the refractive index increases with the electric field intensity, it can act as a positive focusing lens for the electromagnetic wave characterized by an initial transverse intensity profile, as in a laser beam. This phenomenon often occurs when an intense electromagnetic radiation generated by a femtosecond laser propagates through many solids, liquids, and gases. Based on the structure of the medium and the laser intensity, several mechanisms may produce variations in the refractive index which leads to self-focusing. Recently, the development of laser technology has made it possible to observe self-focusing in interactions of intense laser pulses with plasmas [19–22]. The filamentational and modulational instabilities [23–26] are wave-wave interactions, in which two electromagnetic perturbations are added to the original laser pulse. The wave vectors and frequencies of these electromagnetic perturbations are close to the wave vector and frequency of the laser. When the modulation wave vector is perpendicular to the laser wave vector, the light intensity becomes modulated across the laser beam and the term filamentation instability is used. The filamentation instability causes perturbations in the intensity profile of an incident laser beam to grow in amplitude, resulting in the breakup of the beam into many intense filaments. As a matter of fact, self-focusing is a process in which the whole beam is focused and, in the filamentation, the incident laser beam breaks up into numerous small channels, which themselves will be focused.

Another effect which can occur in a dispersive medium is the excitation of soliton waves. In 1966, this phenomenon had been predicted for ion-acoustic waves in a plasma [27]. A soliton is a nonlinear wave which is localized in space and has a steady state form. As a nonlinear wave, its group velocity is proportional to the wave amplitude. Because of the balance of nonlinear and dispersive effects in the medium, the initial shape of the wave can be maintained during the propagation. Some familiar nonlinear equations, such as Kortewegde Vries, nonlinear Schrödinger, and sine-Gordon equations, have soliton form solutions.

Studying the propagation of electromagnetic waves in a magnetized plasma is interesting fundamentally and practically. In a number of physical situations, there is a strong external magnetic field in the plasma. For example, in the magnetosphere of pulsars, the magnetic field strength can be as large as 10^{11} to $10^{13} G$ [28]. Furthermore, in some physical experiments, such as controlled nuclear fusion, the application of a strong external magnetic field is necessary to confine the plasma. Also when an intense laser pulse interacts with a plasma, a strong magnetic field up to 460 MG can be generated via inverse Faraday effect [29,30]. In the quasineutral limit, the nonlinear dynamics of laser pulses propagating in a hot unmagnetized pair plasma has been studied by Shukla *et al.* [31]. Recently, a similar problem for magnetized pair plasma has been studied by Sepehri Javan and Adli [32]. In the present work, we take into account some of the abovementioned nonlinear processes and analyze the relativistic nonlinear evolution of a circularly polarized laser beam propagating along the external magnetic field in a hot magnetized plasma. We pay special attention to the effect of polarization on the nonlinear evolution of the laser pulse. Already, the effect of polarization on the nonlinear dynamics of some phenomena such as self-focusing, modulation, and backward Raman instabilities, etc., has been studied [33–35]. The results are applicable to the laser-plasma interactions in experiments. The organization of this paper is as follows. In Sec. II, the basic assumptions are presented and a nonlinear wave equation is derived. A numerical three-dimensional simulation for the nonlinear evolution of a laser pulse is obtained in Sec. III. Concluding remarks are made in Sec. IV.

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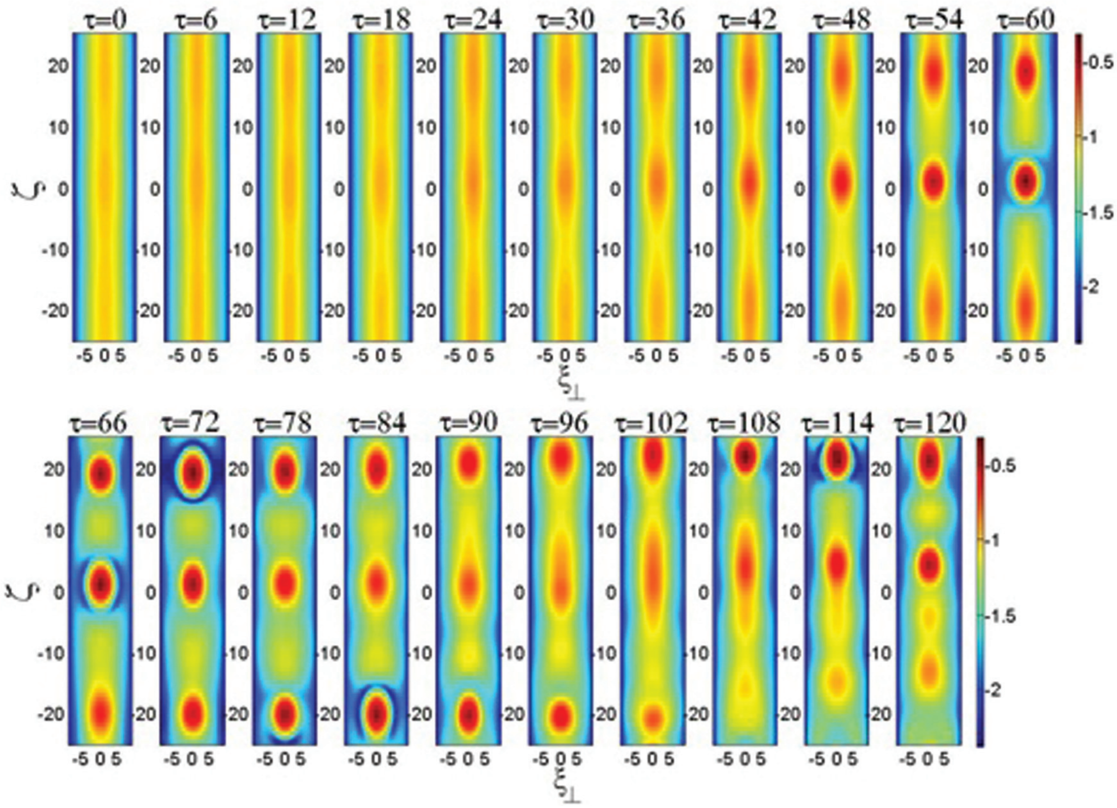

FIG. 1. (Color online) The dimensionless laser amplitude (a) in $\log_{10}$ scale as a function of $\xi_\perp$ and ζ coordinates at different dimensionless times for $\beta = 90$ and $\alpha = 0$.

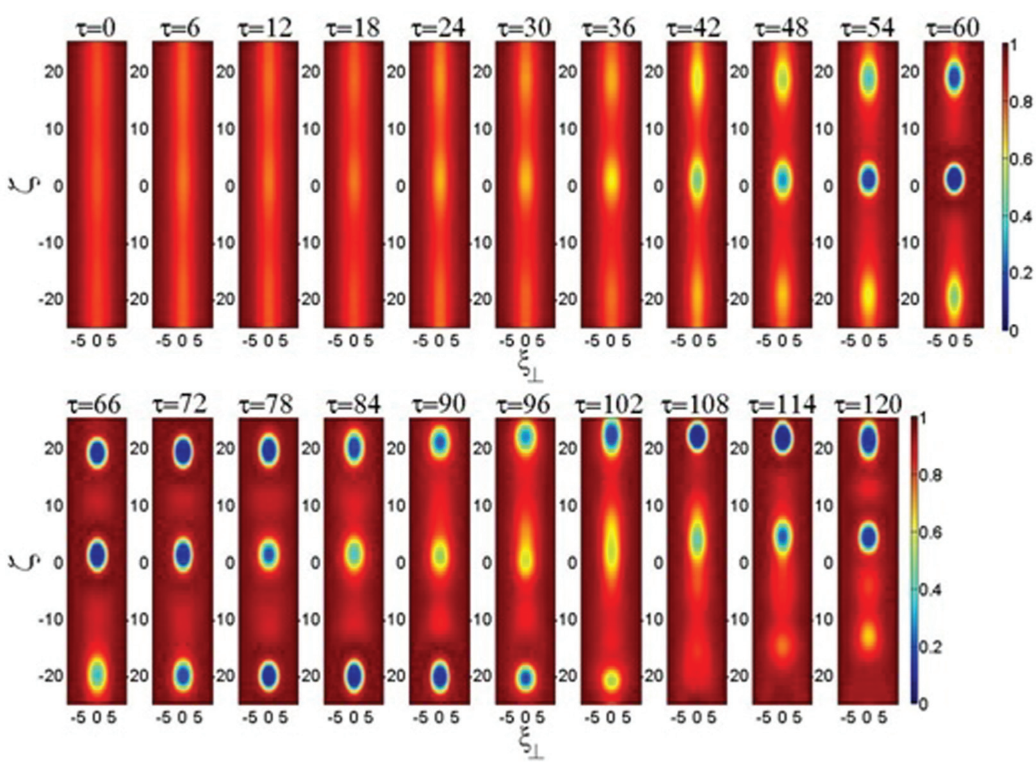

FIG. 2. (Color online) The normalized electron density in $\log_{10}$ scale as a function of $\xi_\perp$ and ζ coordinates at different dimensionless times for $\beta = 90$ and $\alpha = 0$.

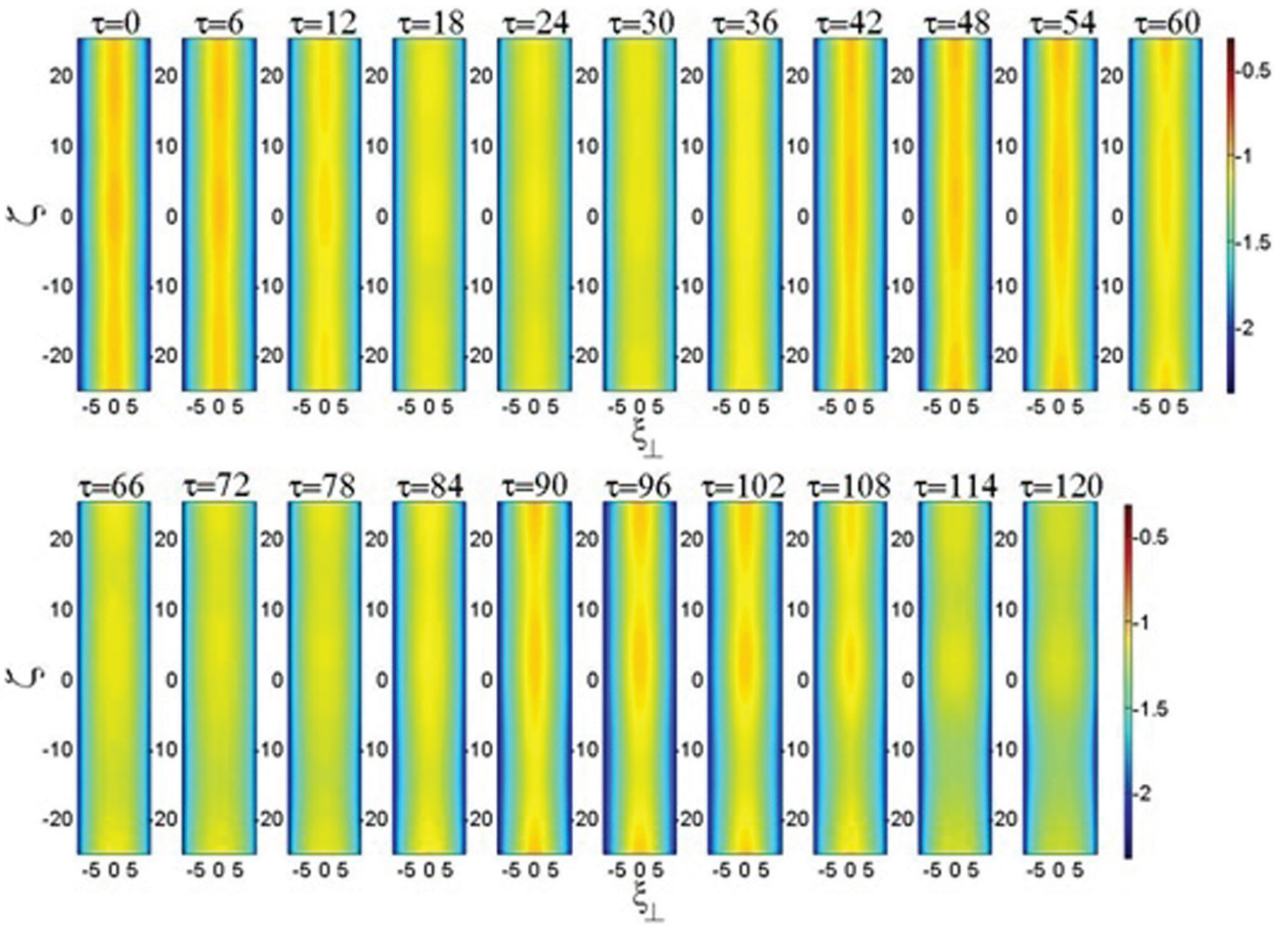

FIG. 3. (Color online) The dimensionless laser amplitude (a) in $\log_{10}$ scale for a left-hand circularly polarized laser as a function of $\xi_\perp$ and ζ coordinates at different dimensionless times for $\beta = 90$ and $\alpha = 0.4$.

II. DERIVING NONLINEAR WAVE EQUATION

We consider the propagation of circularly polarized electromagnetic waves in hot magnetized plasma. Also, we suggest that the external magnetic field is along the z axis: $\mathbf{B_0} = B_0\hat{\mathbf{e}}_z$. For describing nonlinear dynamics of electromagnetic wave interaction with plasma, we define electric and magnetic fields of electromagnetic waves $\mathbf{E}$ and $\mathbf{B}$ through the vector and scalar potentials $\mathbf{A}$ and φ as

$$\mathbf{E} = -\frac{1}{c}\frac{\partial \mathbf{A}}{\partial t} - \nabla\varphi, \quad \mathbf{B} = \nabla \times \mathbf{A}, \tag{1}$$

where c is the speed of light.

In the Coulomb gauge (viz., $\nabla \cdot \mathbf{A} = 0$), using Eqs. (1) in the Maxwell equations, we can write the following equation for large amplitude electromagnetic waves in plasma

$$\frac{1}{c^2}\frac{\partial^2 \mathbf{A}}{\partial t^2} - \nabla^2 A = \frac{4\pi}{c}\mathbf{J}, \tag{2}$$

where, $\mathbf{J} = -n_e e \mathbf{v}_e$ is the current density of the electrons of the plasma, n_e is the density of electrons, $\mathbf{v}_e$ is the electron velocity, and e is the magnitude of the electron charge.

Now, we write the relativistic fluid momentum equation for the electrons:

$$\frac{\partial \mathbf{p}_e}{\partial t} + (\mathbf{v}_e \cdot \nabla)\mathbf{p}_e = -e\left[\mathbf{E} + \frac{1}{c}\mathbf{v}_e \times (\mathbf{B} + \mathbf{B_0})\right] - \frac{1}{n_e}\nabla\Pi, \tag{3}$$

where $\mathbf{p}_e$ is the momentum of the electrons and Π is the pressure of the electrons. Substituting Eqs. (1) into Eq. (3) leads to the following equation:

$$\begin{aligned}\frac{\partial \mathbf{p}_e}{\partial t} &+ \frac{1}{\gamma_e m_{0e}}(\mathbf{p}_e \cdot \nabla)\mathbf{p}_e \\ &= -\frac{e}{c}\frac{\partial A}{\partial t} + e\nabla\varphi - \frac{e}{\gamma_e m_{0e} c}\mathbf{p}_e \times \nabla \times \mathbf{A} - \frac{\omega_c}{\gamma_e}\mathbf{p}_e \times \hat{\mathbf{e}}_z \\ &\quad - k_B T_e \nabla \ln n_e,\end{aligned} \tag{4}$$

where m_0 is the electron rest mass, k_B is the Boltzmann constant, T_e is the temperature of the electrons, $\gamma_e = \sqrt{1 + \frac{p_e^2}{m_{0e}^2 c^2}}$ is the relativistic Lorentz factor of the electrons, and ω_c is the electron cyclotron frequency.

We consider the vector potential of the circularly polarized wave propagating along the external magnetic field as the following:

$$\mathbf{A} = \tfrac{1}{2}\tilde{A}(\hat{\mathbf{e}}_x + i\sigma\hat{\mathbf{e}}_x)\exp(-i\omega_0 t + ik_0 z) + \text{c.c.}, \tag{5}$$

where ω_0 and k_0 are the frequency and the wave number, respectively, $\sigma = +1$ and -1 denotes the right- and left-hand circularly polarized wave, respectively, and also $\tilde{A}(z,t)$ is the slowly varying amplitude that satisfies the following condition:

$$\left|\frac{1}{\omega_0}\frac{\partial \tilde{A}}{\partial t}\right| \ll |\tilde{A}|. \tag{6}$$

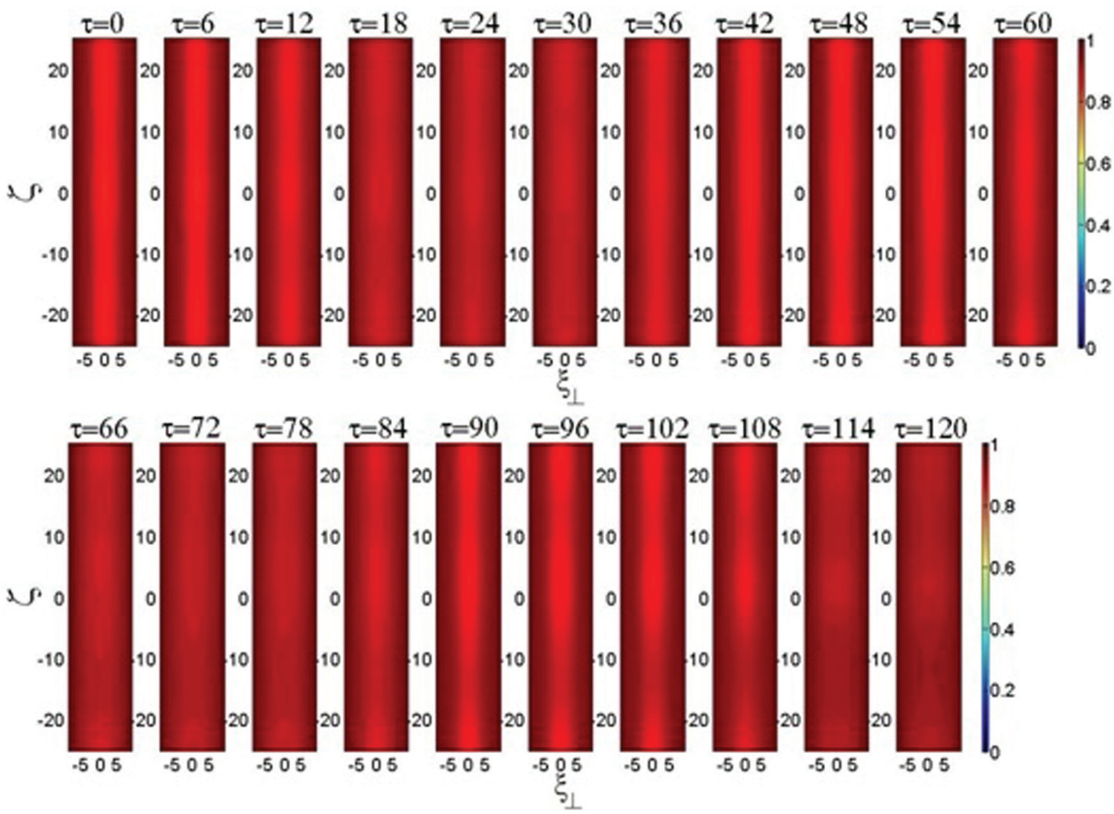

FIG. 4. (Color online) The normalized electron density in $\log_{10}$ scale for a left-hand circularly polarized laser as a function of $\xi_\perp$ and ζ coordinates at different dimensionless times for $\beta = 90$ and $\alpha = 0.4$.

By inserting Eq. (5) into Eq. (4) we find that Eq. (4) is satisfied by [36,37]

$$\bar{\mathbf{p}}_e = \frac{\bar{\mathbf{A}}}{1 - \frac{\sigma\alpha}{\gamma_e}} \tag{7}$$

together with the low-frequency electron momentum balance equation

$$\left[\nabla(\Phi - \psi_p) - \nabla \ln\left(\frac{n_e}{n_{0e}}\right)\right].\hat{\mathbf{e}}_z = 0, \tag{8}$$

where the exact relativistic ponderomotive potential due to the circularly polarized electromagnetic wave in a magnetized plasma is given by

$$\psi_p = \beta_e\left(\gamma_e + \frac{\sigma\alpha}{2\gamma_e^2}\right), \tag{9}$$

$\bar{\mathbf{p}}_e = \frac{\mathbf{p}_e}{m_{0e}c}$ is the normalized electron momentum, $\bar{\mathbf{A}} = \frac{e}{m_{0e}c^2}\mathbf{A}$ is the normalized vector potential, $\Phi = \frac{e\varphi}{k_BT}$ is the normalized scalar potential, $\alpha = \frac{\omega_c}{\omega_0}$, $\beta_e = \frac{c^2}{v_{Te}^2}$, and $v_{Te} = (\frac{k_BT_e}{m_{0e}})^{1/2}$ is the thermal velocity. Integrating Eq. (8), we can write

$$n_e = n_{0e}\exp\left\{\Phi - \beta_e\left[\gamma_e - 1 - \frac{\sigma\alpha|\bar{\mathbf{p}}_e|^2}{2\gamma_e^2}\right]\right\}, \tag{10}$$

where we assume that the plasma is unperturbed at infinity and, accordingly, we have the boundary conditions $n_e = n_{0e}$, $\Phi \to 0$, and $\bar{p}_e \to 0$ at $|z| \to \infty$.

We suppose that the ion slow motion is nonrelativistic. When the phase velocity of the ion fluctuations is much smaller than the thermal velocity, the quasistatic ion number density follows from a balance of the ion thermal pressure and the slow field. Since the quasistatic interaction arises on a very slow time scale (typically larger than the ion plasma period $\omega_{pi}^{-1} = (\frac{4\pi n_{0i}e^2}{m_{0i}})^{-\frac{1}{2}}$, where n_{0i} and m_{0i} are the unperturbed density of ions and the rest mass of ions, respectively), one may assume an isothermal equation of state for ions and obtain the ion number density expression [36]

$$n_i = n_{0i}\exp(-\delta\Phi), \tag{11}$$

where $\delta = \frac{T_e}{T_i}$ is the ratio of the electron temperature to the ion temperature.

In the quasineutral limit, when $n_e = n_i$ (and also $n_{0e} = n_{0i} = n_0$) Eqs. (10) and (11) yield to the following result:

$$n_e = n_i = n_0\exp\left[-\kappa\left(\gamma_e - 1 - \sigma\frac{\alpha}{2}\frac{|\bar{\mathbf{p}}_e|^2}{\gamma_e^2}\right)\right], \tag{12}$$

where $\kappa = \frac{\beta_e}{1+\delta^{-1}}$. In physical units, from Eq. (7) for the velocity of the electrons we obtain

$$\mathbf{v}_e = \frac{e}{m_{0e}c}\frac{\mathbf{A}}{\gamma_e - \sigma\alpha}, \tag{13}$$

Also, for the electron Lorentz factor we can approximately write

$$\gamma_e \approx \sqrt{1 + \frac{|\bar{\mathbf{A}}|^2}{(1-\sigma\alpha)^2}}, \tag{14}$$

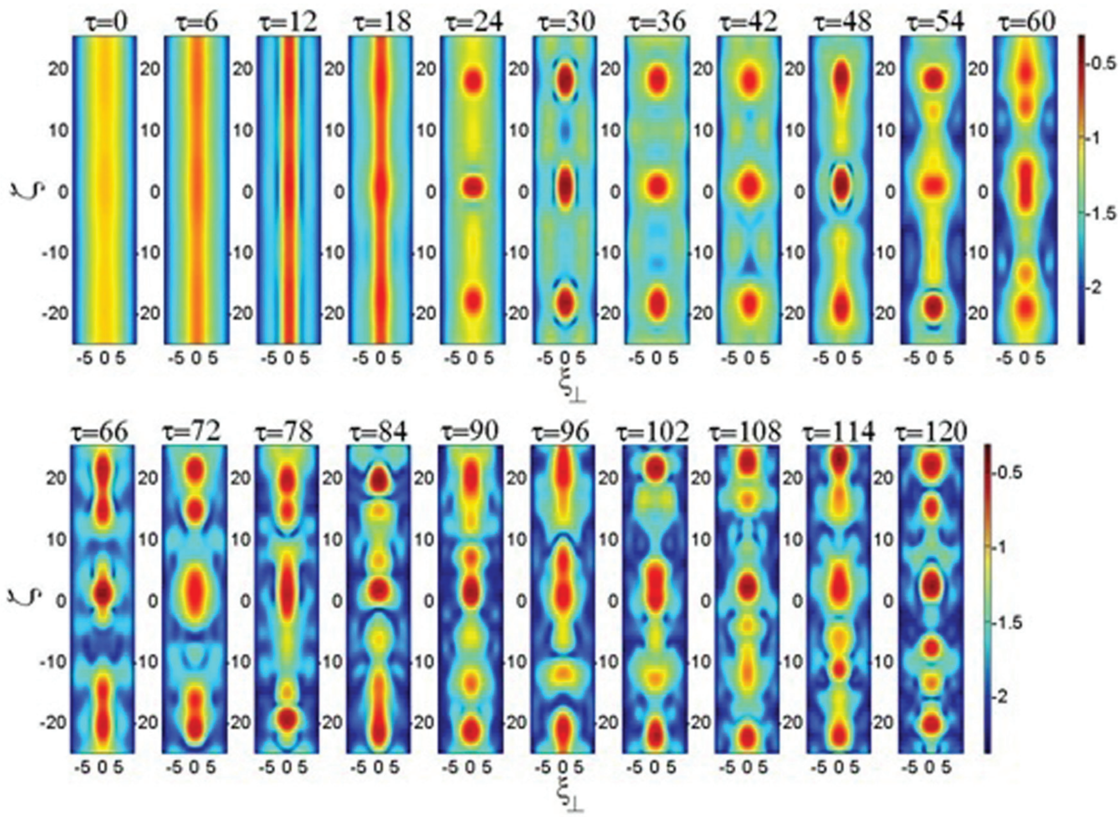

FIG. 5. (Color online) The dimensionless laser amplitude (a) in $\log_{10}$ scale for a right-hand circularly polarized laser as a function of $\xi_\perp$ and ζ coordinates at different dimensionless times for $\beta = 90$ and $\alpha = 0.4$.

Now, taking Eqs. (12) and (13) into consideration, we can derive the nonlinear current density as the following:

$$-\frac{4\pi}{c}\mathbf{J} = \frac{\omega_p^2}{c^2}\frac{\mathbf{A}}{(\gamma_e - \sigma\alpha)}\exp\left[-\kappa\left(\gamma_e - 1 - \frac{\sigma\alpha}{2}\frac{|\bar{\mathbf{p}}_e|^2}{\gamma_e^2}\right)\right], \tag{15}$$

where $\omega_p = \sqrt{\frac{4\pi n_0 e^2}{m_{0e}}}$ is the electron Langmuir frequency. For weakly relativistic laser intensity, when $|\bar{\mathbf{A}}|^2, |\bar{\mathbf{p}}_e|^2 \ll 1$ and $\gamma_e \approx 1 + \frac{1}{2}|\bar{\mathbf{p}}_e|^2$, we can simplify the current density as the following:

$$-\frac{4\pi}{c}\mathbf{J} \approx \frac{\omega_p^2}{c^2}\mathbf{A}P\exp\left(-\frac{\kappa}{2}\frac{|\bar{\mathbf{A}}|^2}{(1-\sigma\alpha)}\right), \tag{16}$$

where

$$P = \frac{1}{(1-\sigma\alpha)}\left(1 - \frac{|\bar{\mathbf{A}}|^2}{2(1-\sigma\alpha)^3}\right). \tag{17}$$

Substituting the nonlinear current density from Eq. (16) and the vector potential in the form of Eq. (5) into Eq. (2) leads to the following equation for the electromagnetic wave envelope:

$$\frac{\partial^2\tilde{A}}{\partial t^2} - c^2\frac{\partial^2\tilde{A}}{\partial z^2} - 2i\omega_0\frac{\partial\tilde{A}}{\partial t} - 2ic^2k_0\frac{\partial\tilde{A}}{\partial z} + \left[-\omega_0^2 + k_0^2c^2 + \omega_p^2 P\exp\left(-\frac{\kappa}{2}\frac{|\bar{\mathbf{A}}|^2}{(1-\sigma\alpha)}\right)\right]\tilde{A} = 0. \tag{18}$$

In the last term of Eq. (18), the coefficient of $\tilde{A}$ is the nonlinear dispersion relation. If we neglect the interaction between the plasma and the electromagnetic wave, i.e., when $\tilde{A}$ is constant, we can derive a nonlinear dispersion relation of hot magnetized plasma as follows:

$$k_0^2c^2 - \omega_0^2 + \frac{\omega_p^2}{(1-\sigma\alpha)}\left(1 - \frac{|\bar{\mathbf{A}}|^2}{2(1-\sigma\alpha)^3}\right) \times \exp\left(-\frac{\kappa}{2}\frac{|\bar{\mathbf{A}}|^2}{(1-\sigma\alpha)}\right). \tag{19}$$

In the linear limit Eq. (19) reduces to the well-known linear dispersion relation for right- and left-hand circularly polarized electromagnetic waves in magnetized plasma [38]:

$$k_0 = \frac{\omega_0}{c}\left(1 - \frac{\omega_p^2}{\omega_0(\omega_0 - \sigma\omega_c)}\right)^{\frac{1}{2}}. \tag{20}$$

We assume that ω_0 and k_0 satisfy the linear dispersion of Eq. (20). By applying the condition of slowly varying amplitude to Eq. (18) we obtain the following equation:

$$i\left(\frac{\partial\tilde{A}}{\partial t} + v_g\frac{\partial\tilde{A}}{\partial z}\right) + \frac{c^2}{2\omega_0}\frac{\partial^2\tilde{A}}{\partial z^2} + \frac{\omega_p^2}{\omega_0}D_{\mathrm{NL}}\tilde{A} = 0, \tag{21}$$

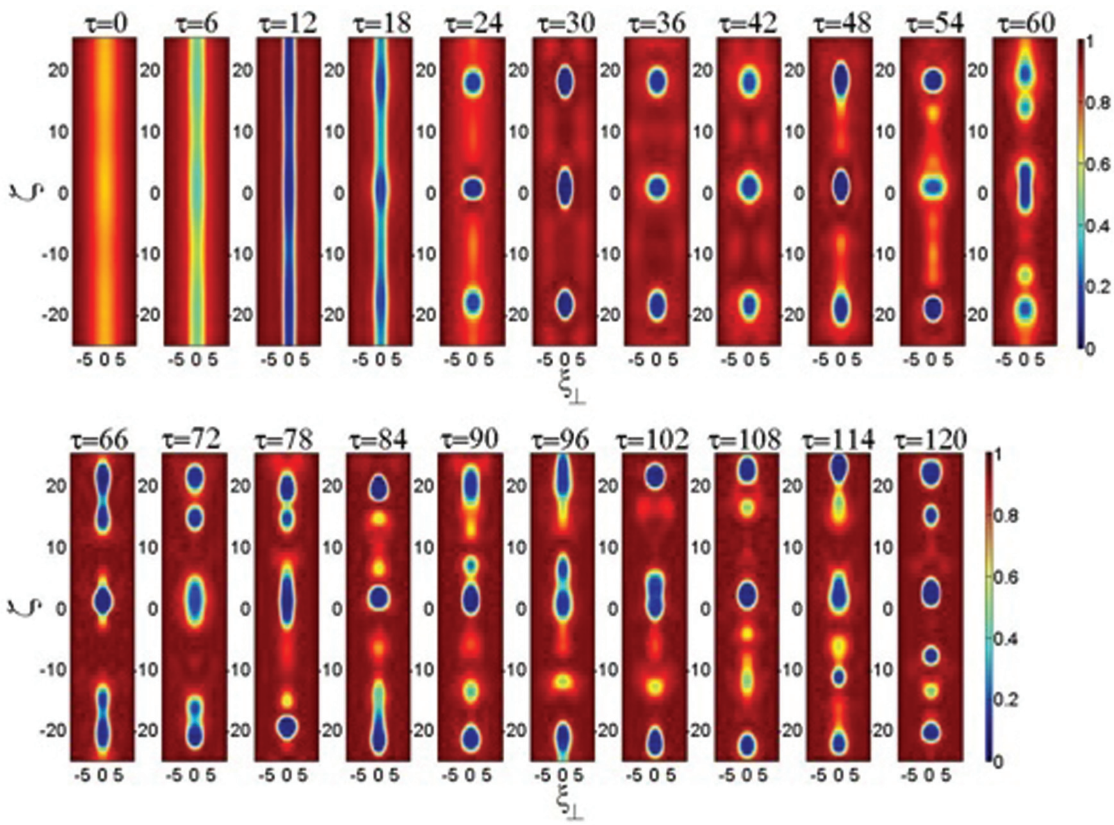

FIG. 6. (Color online) The normalized electron density in $\log_{10}$-scale for a right-hand circularly polarized laser as a function of $\xi_\perp$ and ζ coordinates at different dimensionless times for $\beta = 90$ and $\alpha = 0.4$.

where $v_g = \frac{k_0 c^2}{\omega_0}$ is the group velocity and

$$D_{\rm NL} = \frac{1}{2(1-\sigma\alpha)}\left[1 - \left(1 - \frac{|\bar{\mathbf{A}}|^2}{2(1-\sigma\alpha)^3}\right)\right.$$
$$\left.\times \exp\left(-\frac{\kappa}{2}\frac{|\bar{\mathbf{A}}|^2}{(1-\sigma\alpha)}\right)\right]. \tag{22}$$

By introducing the following dimensionless variables

$$\tau = \frac{\omega_p^2}{\omega_0}t, \quad U_g = \frac{\omega_0}{\omega_p}\frac{v_g}{c}, \quad \xi = \frac{\omega_p}{c}z - U_g\tau, \quad a = \frac{e}{m_{0e}c^2}\tilde{A}, \tag{23}$$

we can write Eq. (21) in the form

$$i\frac{\partial a}{\partial t} + \frac{1}{2}\frac{\partial^2 a}{\partial \xi^2} + D_{\rm NL}a = 0. \tag{24}$$

III. NONLINEAR EVOLUTION OF LASER PULSE

In order to investigate the spatial-temporal evolution of an intense laser beam in a plasma, we have numerically solved the modified nonlinear Schrödinger equation, Eq. (24), for the amplitude of the dimensionless vector potential and have found the electron (ion) density given by

$$n_e = n_i = n_0 \exp\left(-\frac{\kappa}{2}\frac{|\bar{\mathbf{A}}|^2}{(1-\sigma\alpha)}\right). \tag{25}$$

We consider the axial symmetry around the direction of the external magnetic field. The initial condition for a modulated laser pulse is considered to be

$$a|_{\tau=0} = 0.1\left[1 + 0.02\sin\left(\frac{2\pi\zeta}{L_\zeta}\right) + 0.02\cos\left(\frac{4\pi\zeta}{L_\zeta}\right)\right.$$
$$\left. + \; 0.02\cos\left(\frac{6\pi\zeta}{L_\zeta}\right)\right]\exp\left(-\frac{\xi_\perp^2}{32}\right), \tag{26}$$

where $L_\zeta = 16\pi$ is the simulation box dimensionless length and $\xi_\perp$ is the dimensionless radial space coordinate. For all cases we set $\beta = 90$ (or $T_e = T_i = 5.68$ keV).

Figures 1 and 2 demonstrate the spatial-temporal evolution of the normalized laser pulse amplitude (a) and also the normalized electron density (n_e/n_0) for unmagnetized plasma. The first panels of Figs. 1 and 2 indicate the initial distribution of the amplitude according to Eq. (26)and the corresponding initial electron density, respectively. At the earlier stages ($\tau = 3$–12), the whole of the laser pulse concentrates radially and the pulse self-focusing in the radial direction can be seen. As the pulse focuses, the electrons are being pushed out radially because of the ponderomotive force. Localization of the pulse amplitude along the propagation direction due to the modulation instability and its self-focusing in the radial direction yield the ball-shaped structures or filaments. In the panels corresponding to $\tau = 18$–60 of these figures one can see the formation of electromagnetic filaments. Consequently, electron holes are created where the wave envelope is trapped. At the center of each filament, the amplitude of the laser

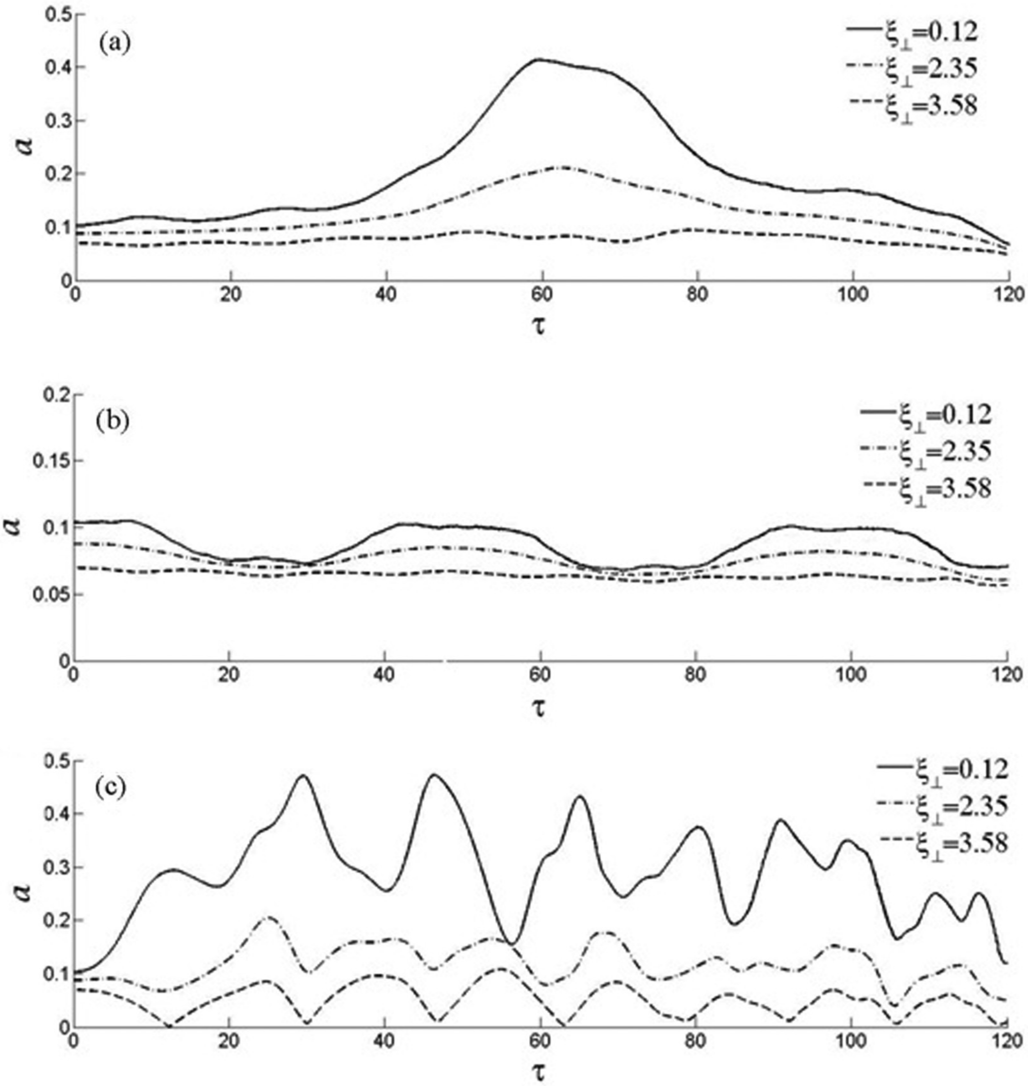

FIG. 7. Variation of laser beam amplitude versus time at $\zeta = 0$ and three different $\xi_\perp$: (a) for unmagnetized plasma, (b) for magnetized plasma with $\alpha = 0.4$ and a left-hand circularly polarized wave, and (c) for magnetized plasma with $\alpha = 0.4$ and a right-hand circularly polarized wave.

temporally grows and reach a maximum; after this the amplitude decreases. Again the pulse focuses radially and azimuthally and more filaments are created. Such a scenario is repeated for all the forthcoming times and the structure of the laser pulse becomes more irregular and more complicated after each iteration.

In order to highlight the effect of the magnetic field on the nonlinear dynamics of the laser, in Figs. 3–6 we have considered the magnetized cases for both right- and left-hand polarizations for $\alpha = 0.4$. We can see that the growth rate of modulation and filamentation instabilities and also the quality of self-focusing increase with the application of an external magnetic field on the right-hand polarization. Inversely, for the left-hand polarization, the growth rate of instabilities and the temporal rate of self-focusing evolution decrease by using a magnetic field. Therefore, the application of an external magnetic field improves the nonlinearity of plasma for right-hand polarization and reduces it for left-hand polarization [33,34]. Physically, the right-hand wave drives electrons in the direction of their cyclotron motion. In this polarization, the increase in magnetic field causes the increase in the transverse velocity of electrons and it leads to the increase in the nonlinear current density or the nonlinearity of plasma. The rotation sense of the left-hand polarization is opposite to the electrons' cyclotron motion and the velocity of the electrons (and or consequently, the nonlinearity of the plasma medium) decreases with an increase in the external magnetic field. Furthermore, the concentration of radiation energy around the symetry axis is more noticeable for the right-hand polarization. As is clear from the last panels of Figs. 5 and 6, the structures of the laser intensity and the electron density distrbution become very complicated in comparision with the unmagnetized plasma. Each of the previous localized ball-like distributions of laser amplitude divides into numerous spindlelike substructures and the same happens for the corresponding electron holes.

To clarify the role of magnetization of plasma in the nonlinear dynamics of laser, in Figs. 7 and 8 we have plotted

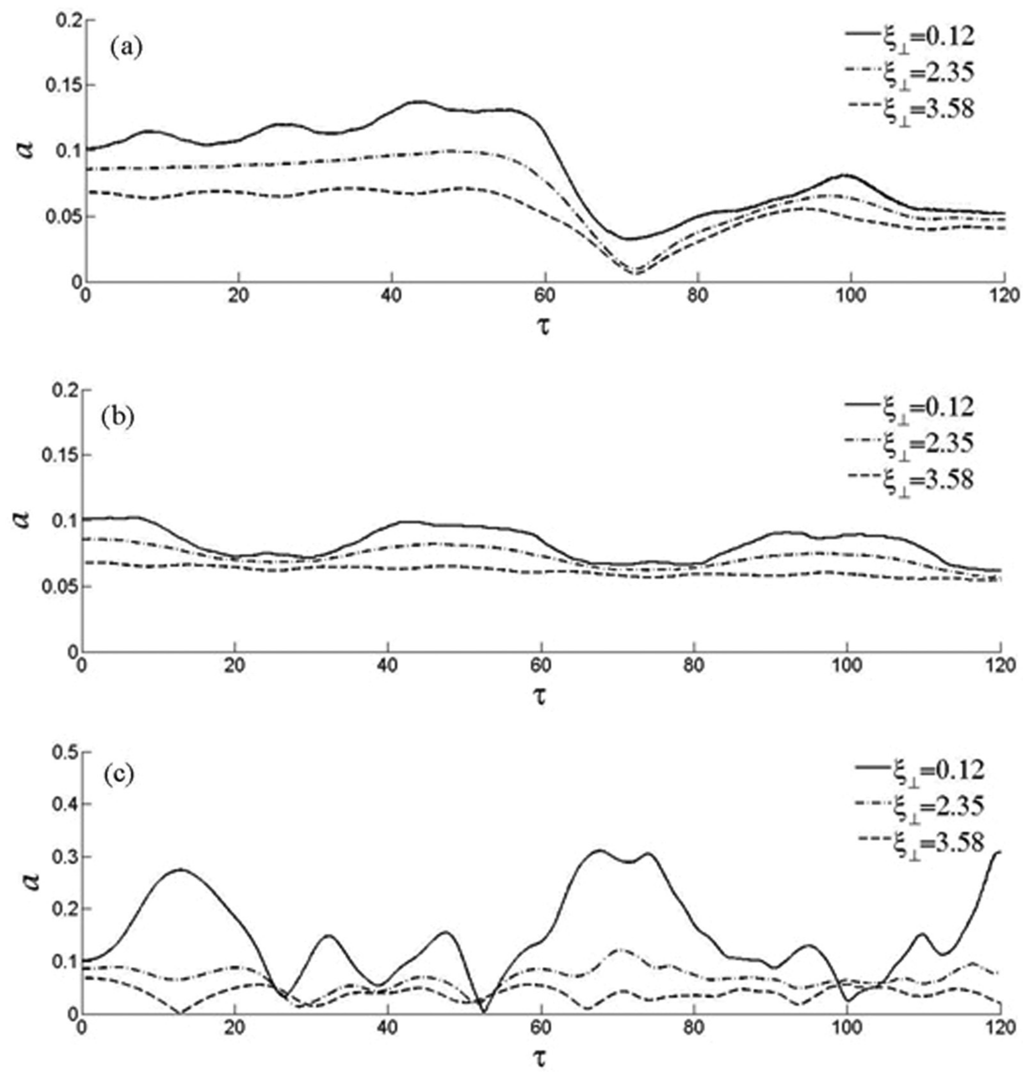

FIG. 8. Variation of laser beam amplitude versus time at $\zeta = 15.1$ and three different $\xi_\perp$: (a) for unmagnetized plasma, (b) for magnetized plasma with $\alpha = 0.4$ and a left-hand circularly polarized wave, and (c) for magnetized plasma with $\alpha = 0.4$ and a right-hand circularly polarized wave.

the variation of the laser amplitude with time at some fixed points of space. Figure 7 represents the temporal variation of amplitude at three different radial coordinates $\xi_\perp$ at the origin $\zeta = 0$ for unmagnetized and magnetized cases. It is clear that exerting an external magnetic field accelerates nonlinear processes of self-focusing and modulation of the laser for the right-hand polarization and decelerates it for the left-hand polarization. Also the applied magnetic field causes the pulse to oscillate more stochastically with respect to time for the right-hand polarization. For the left-hand polarization, temporal oscillation of the laser amplitude is around the initial amplitude of $a_0 = 0.1$. Figure 8 demonstrates the variation of the laser amplitude versus time for the points near to the boundary of the simulation box at $\zeta = 15.1$ and three different $\xi_\perp$ for the magnetized and unmagnetized plasma cases. For all cases, the appearance of self-focusing and modulation processes is evident in the first stage. However, for the magnetized plasma and the right-hand polarization the temporal growth rate of these phenomena is greater than the other cases. After this stage when the filamentation instability starts, temporal oscillations of the amplitude in space for the magnetized plasma and the right-hand polarization become more noticeable.

IV. CONCLUSIONS

In this work, we have investigated the relativistic nonlinear dynamics of a circularly polarized laser pulse propagating along the external magnetic field in a plasma. We obtained a nonlinear modified Schrödinger equation, in a quasineutral approximation, which is valid for high-temperature plasmas. For a three-dimensional model, we have simulated the nonlinear dynamics of the laser pulse propagating in magnetized plasma. Our simulations showed that the magnetization of plasma accelerates the temporal evolution of nonlinear processes such as self-focusing, modulational, and filamentational instabilities for the right-hand polarization and decelerates it for the left-hand polarization. Furthermore, in a magnetized plasma and right-hand polarization, temporal and spatial oscillations of the laser amplitude are more irregular and stochastic.

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