J. Plasma Phys. (2017), *vol.* 83, 655830401
doi:10.1017/S0022377817000460

Nonlinear interaction of intense left- and right-hand polarized laser pulse with hot magnetized plasma

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(Received 11 March 2017; revised 31 May 2017; accepted 31 May 2017)

In this article, self-focusing of an intense circularly polarized laser pulse in the presence of an external oblique magnetic field in hot magnetized plasma, using Maxwell's equations and the relativistic fluid momentum equation, is studied. An envelope equation governing the spot size of the laser beam for both of left- and right-hand polarizations has been derived and the effects of the plasma temperature and oblique magnetic field on the electron density distribution of hot plasma with respect to variation of the normalized laser spot size has been investigated. Numerical results depict that in right-hand polarization, self-focusing of the laser pulse along the propagation direction in hot magnetized plasma becomes better and more compressed with increasing θ. Inversely, in left-hand polarization, increase of θ in an oblique magnetic field leads to enhancement of the spot size and reduction self-focusing. Besides, in the plasma density profile, self-focusing of the laser pulse improves in comparison with no oblique magnetic field. Also it is shown that plasma temperature has a key role in the laser spot size, normalized laser output power and the variation of plasma density.

Key words: magnetized plasmas, plasma nonlinear phenomena, plasma waves

1. Introduction

The nonlinear propagation of intense laser pulses within plasmas has drawn the attention of researchers since the interaction of intense laser pulses with plasmas is associated with a wide range of applications including plasma wakefields (Tajima & Dawson 1979; Fontana & Pantell 1983; Sprangle *et al.* 1988), inertial confinement fusion (Roth *et al.* 2001), fusion harmonics generation (Amendt, Eder & Wilks 1991; Shukla 1999), magnetic field generation, X-ray lasers (Burnett & Corkum 1989; Eder *et al.* 1994; Tabak *et al.* 1994; Lemoff *et al.* 1996) and laser fusion (Tabak *et al.* 1994; Deutsch *et al.* 1996; Regan *et al.* 1999) etc. Furthermore, intense laser pulses can lead to instabilities including Raman and Brillouin instabilities and modulational and filamentational instabilities in plasmas (Benjamin & Feir 1967; Max, Arons & Langdon 1974; Kruer 1988; McKinstrie & Bingham 1992; Esarey *et al.* 1996;

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Mori 1997). In the laser–plasma interaction, self-focusing is an optical phenomenon that can occur as a result of the intensity dependent refractive index. This phenomenon generally occurs when a beam of light having a non-uniform transverse intensity distribution propagates through a material such as a plasma. Under this condition, the plasma can act as a positive focusing lens. Self-focusing has a key role in optical materials because the intensity at the focal spot of the self-focused beam is often sufficiently large and leads to optical damage of the material (Boyd 2003). Although self-focusing is a conventional subject of nonlinear optics, lately, with the development of technologies associated with lasers, the observation of self-focusing in the interaction of intense laser pulses with plasmas has been made possible (Monot *et al.* 1995; Krushelnick *et al.* 1997; Eslami & Nami 2016; Patil & Takale 2016; Saedjalil & Jafari 2016). In the laser–plasma interactions there are a variety of mechanisms, such as ponderomotive effects and thermal relativistic effects that can create variations of the refractive index which leads to self-focusing. Ponderomotive self-focusing is caused by the ponderomotive force which pushes the electrons away from the region of highest laser intensity leaving behind a region of lowered electron density. Consequently, increasing the refraction index leads to self-focusing of the propagating intense laser pulse. In addition, thermal self-focusing (TSF) is a result of collisional heating of plasma due to the propagation of an intense laser pulse in the plasma. In TSF, density perturbations arise due to temperature gradients associated with heating by a non-uniform laser field. Enhancement in the temperature causes an increase in the refractive index and more heating (Perkins & Valeo 1974). Recently, the self-focusing issue has been studied by several researchers, both theoretically and experimentally. Patil *et al.* (2013) studied propagation of the Gaussian laser beam in a plasma. They investigated the nonlinear differential equation for the beam width parameter using a parabolic equation approach and solved it numerically. They found that the ponderomotive self-focusing contributed in the relativistic self-focusing of the laser beam. Also, impacts of plasma electron temperature, relative density parameter and intensity parameter on the propagation of the laser beam have been studied. Nanda *et al.* (Wani & Kant 2014) considered self-focusing of a Hermite–Cosh–Gaussian laser beam under density transition for different modes in a plasma.

Khachatrian & Sukhorukov (1971) presented some aspects of thermal self-focusing. They have shown that the shape of the focus depends on the time constant associated with the change of refractive index. Walia & Singh (2011) investigated relativistic self-focusing of a Gaussian laser beam by the moment theory approach in a plasma. It was found that, between the paraxial and the moment theory at lower intensities there is an agreement. Esarey *et al.* (1997) studied the propagation of intense optical beams in gases undergoing ionization. A fundamental Gaussian and a higher-order radially polarized beam as two types of optical beam modes were presented. Borisov *et al.* (1992) calculated, using the nonlinear Schrödinger equation, relativistic–ponderomotive self-channelling of intense ultrashort laser pulses in a medium. They have analysed the self-channelling of an intense ultrashort laser pulse in plasma as the result of a change in the refractive index due to the relativistic increase in the mass of the electrons. Kant, Saralch & Singh (2011) considered the nonlinear propagation of a short laser pulse in a slowly varying upward plasma density ramp. They observed that with and without the plasma density ramp the spot size as a function of the propagation distance has an oscillatory nature. As a result, the presence of the plasma density ramp leads to an increase in self-focusing. Wang & Zhou (2011) studied propagation characters of a Gaussian laser beam and the plasma density distribution in the collisionless and non-relativistic regime in a cold plasma.

This paper is organized in five sections including the introduction in § 1. In § 2, we derive the nonlinear wave equation and governing equations in the weakly relativistic regime for a hot magnetized plasma in the presence of an external oblique magnetic field. In § 3, the equation governing the laser spot size has been found using the source dependent expansion (SDE) method for self-focusing of an electromagnetic wave. In § 4, the numerical results for the self-focusing properties of a circularly polarized wave in a hot magnetized plasma for left- and right-handed polarizations in the presence of an external oblique magnetic field are discussed. Finally, the conclusions are presented in § 5.

2. Physical method

Consider the propagation of a circularly polarized electromagnetic wave in a hot magnetized plasma in the weakly relativistic regime. Moreover, an oblique magnetic field in the plasma is employed along the z and y directions,

$$\boldsymbol{B}=\boldsymbol{B}_0(\cos\theta\hat{\boldsymbol{e}}_z+\sin\theta\hat{\boldsymbol{e}}_y), \tag{2.1}$$

where $\boldsymbol{B}_0$ is the external magnetic field strength at $\theta=0$. Here θ is angle of magnetic field. To describe the interactions between the electromagnetic wave and the plasma, we employ Maxwell's equations and the relativistic fluid momentum equation as follows,

$$\boldsymbol{E}=-\frac{1}{c}\frac{\partial\boldsymbol{A}}{\partial t}-\nabla\varphi \tag{2.2}$$

$$\boldsymbol{B}=\nabla\times\boldsymbol{A} \tag{2.3}$$

$$\nabla\times\boldsymbol{B}=\frac{4\pi}{c}\boldsymbol{J}+\frac{1}{c}\frac{\partial\boldsymbol{E}}{\partial t} \tag{2.4}$$

$$\boldsymbol{J}=-n_e e\boldsymbol{v}_e. \tag{2.5}$$

Using (2.2)–(2.4), the above equations will be expressed as

$$-\frac{1}{c^2}\frac{\partial^2\boldsymbol{A}}{\partial t^2}-\nabla^2\boldsymbol{A}=\frac{4\pi}{c}\boldsymbol{J}, \tag{2.6}$$

where $\boldsymbol{E}$, $\boldsymbol{B}$ are electric and magnetic fields of electromagnetic wave, $\boldsymbol{A}$ is the vector potential, c denotes the speed of light in vacuum, $\boldsymbol{J}$ is the current density of electrons in the plasma, n_e is the density of electrons, e is the magnitude of electron charge and $\boldsymbol{v}_e$ is the electron velocity. As known, the relativistic fluid momentum equation for electrons is,

$$\frac{\partial\boldsymbol{p}_e}{\partial t}+(\boldsymbol{v}_e\boldsymbol{\cdot}\nabla)\boldsymbol{p}_e=-e\left[\boldsymbol{E}+\frac{1}{c}\boldsymbol{v}_e\times(\boldsymbol{B}+\boldsymbol{B}_0)-\frac{1}{n_e}\nabla p\right] \tag{2.7}$$

in which $\boldsymbol{p}_e$ and p are momentum and pressure of electrons respectively. Inserting for $\boldsymbol{E}$ and $\boldsymbol{B}$ from (2.2) and (2.3) into the relativistic fluid momentum equation (2.7), it is obtained as (Abedi-Varaki & Jafari 2017),

$$\begin{aligned}\frac{\partial\boldsymbol{p}_e}{\partial t}+\frac{1}{\gamma_e m_{0e}}(\boldsymbol{p}_e\boldsymbol{\cdot}\nabla)\boldsymbol{p}_e &= \frac{e}{c}\frac{\partial\boldsymbol{A}}{\partial t}+e\nabla\varphi+\frac{e}{\gamma_e m_{0e}}[(\boldsymbol{p}_e\boldsymbol{\cdot}\nabla)\boldsymbol{A}-\boldsymbol{p}_e\boldsymbol{\cdot}(\nabla\boldsymbol{A})]\\ &\quad -\frac{\omega_c}{\gamma_e}\boldsymbol{p}_e\times(\cos\theta\hat{\boldsymbol{e}}_z+\sin\theta\hat{\boldsymbol{e}}_y)-k_B T_e\nabla\ln n_e,\end{aligned} \tag{2.8}$$

where $\omega_c = eB_0/m_{0e}c$ is the electron cyclotron frequency, k_B is the Boltzmann constant, m_{0e} is the electron rest mass and $\gamma_e = \sqrt{1 + p_e^2/m_{0e}^2c^2}$ denotes the relativistic Lorentz factor of an electron. Now, consider a circularly polarized wave propagating along the external magnetic field which is proposed to be in the z direction and described by the transverse component of its vector potential,

$$\boldsymbol{A} = \tfrac{1}{2}\tilde{A}(\hat{\boldsymbol{e}}_x + \mathrm{i}\sigma\hat{\boldsymbol{e}}_y)\exp(-\mathrm{i}\omega_0 t + \mathrm{i}k_0 z) + \text{c.c.} \tag{2.9}$$

Where $\tilde{A}(z, t)$ is the pulse envelope, generally a complex valued function of space, ω_0 is frequency and k_0 is the wavenumber. Also $\sigma = \pm 1$ is the corresponding right- and left-handed circularly polarized electromagnetic wave, respectively. Substituting (2.9) into (2.8), (2.8) is satisfied by (Rao, Shukla & Yu 1984)

$$\bar{\boldsymbol{P}}_e = \frac{\bar{\boldsymbol{A}}}{1 - \dfrac{\alpha\sigma(\cos\theta + \sin\theta)}{\gamma_e}}. \tag{2.10}$$

If (2.9) conjugate with the low frequency electron momentum balance equation, then we have (Rao *et al.* 1984)

$$\left[\nabla(\Phi - \Lambda_p) - \nabla\ln\left(\frac{n_e}{n_{0e}}\right)\right]\cdot(\cos\theta\hat{\boldsymbol{e}}_z + \sin\theta\hat{\boldsymbol{e}}_y) = 0 \tag{2.11}$$

in which (Shukla, Bharuthram & Tsintsadze 1988)

$$\Lambda_p = \beta_e\left(\gamma_e + \frac{\alpha\sigma}{2\gamma_e^2}\right) \tag{2.12}$$

and $\bar{\boldsymbol{p}}_e = \boldsymbol{p}_e/m_{0e}c$, $\bar{\boldsymbol{A}} = e/m_{0e}c^2\boldsymbol{A}$, $\Phi = e\varphi/k_BT_e$, $v_{Te}^2 = k_BT/m_{0e}$ are the normalized electron momentum, normalized vector potential, normalized scalar potential and thermal velocity, respectively. In addition, $\alpha = \omega_c/\omega_0$ and $\beta_e = c^2/v_{Te}^2$ are dimensionless parameters. Equation (2.11) can be written as follows,

$$n_e = n_{0e}\exp\left\{\Phi - \beta_e\left[\gamma_e - 1 - \frac{\alpha\sigma|\bar{\boldsymbol{P}}_e|^2}{2\gamma_e^2}\right]\right\}. \tag{2.13}$$

Furthermore, the plasma is proposed to be unperturbed at $|z| \to \infty$. Consequently, the boundary conditions at infinity are $n_e = n_{0e}$ and $\Phi = \bar{\boldsymbol{p}}_e = 0$. Here the ions maintain a quasi-static equilibrium and the ion number density is explained by the equation

$$n_i = n_{0i}\exp(-\eta\Phi), \tag{2.14}$$

where $\eta = T_e/T_i$ is the proportion of electron temperature to ions temperature. In the quasi-neutral limit for a weakly relativistic intense laser pulse we have,

$$n_{0e} = n_{0i} = n_0. \tag{2.15}$$

Substituting, equations (2.14) and (2.12) into (2.13), the following relation can be derived (Rao *et al.* 1984),

$$n_e = n_{0e}\exp\left[-\Gamma\left(\Phi - \left(\gamma_e - 1 - \frac{\alpha\sigma|\bar{\boldsymbol{P}}_e|^2}{2\gamma_e^2}\right)\right)\right], \tag{2.16}$$

where $\varGamma=\beta_e/1+\eta^{-1}$. Using (2.10) and $\boldsymbol{p}=\gamma_e m_{0e}\boldsymbol{v}_e$ for the velocity of the electrons we obtain the following relation,

$$\boldsymbol{V}_e=\frac{e}{m_{0e}c}\frac{\boldsymbol{A}}{(\gamma_e-\alpha\sigma(\cos\theta+\sin\theta))}. \tag{2.17}$$

Approximately, the electron Lorentz factor can be written as,

$$\gamma_e\approx\left(1+\frac{|\bar{\boldsymbol{A}}|^2}{(1-\alpha\sigma(\cos\theta+\sin\theta))^2}\right)^{1/2}. \tag{2.18}$$

Since the current density is $\boldsymbol{J}=n_e e\boldsymbol{v}_e$, compounding (2.16) and (2.17) for nonlinear current density, it is obtained that,

$$\frac{-4\pi}{c}J=\frac{\omega_p^2}{c^2}\exp\left(-\varGamma\left(\gamma_e-1-\frac{\alpha\sigma}{2}\frac{|\bar{\boldsymbol{p}}_e|^2}{\gamma_e^2}\right)\right)\left(\frac{\boldsymbol{A}}{(\gamma_e-\alpha\sigma(\cos\theta+\sin\theta))}\right), \tag{2.19}$$

where $\omega_p=\sqrt{4\pi n_e e^2/m_e}$ is the plasma frequency. In the weakly relativistic regime, when $|\bar{\boldsymbol{A}}|^2$, $|\bar{\boldsymbol{p}}_e|^2\leqslant 1$ and $\gamma_e\approx 1+|\bar{\boldsymbol{p}}_e|^2/2$, the current density can be simplified as follows

$$\frac{-4\pi}{c}J\approx\frac{\omega_p^2}{c^2}\boldsymbol{A}P\exp\left(-\frac{\varGamma|\bar{\boldsymbol{A}}|^2(1-\alpha\sigma)}{2(1-\alpha\sigma(\cos\theta+\sin\theta))^2}\right), \tag{2.20}$$

where

$$P=\frac{1}{(1-\alpha\sigma(\cos\theta+\sin\theta))}\left(1-\frac{|\bar{\boldsymbol{A}}|^2}{2(1-\alpha\sigma)^3}\right). \tag{2.21}$$

Using (2.6), (2.8) and (2.20) to derive the governing equation for the electromagnetic wave envelope, we obtain,

$$\begin{aligned}&\frac{\partial^2\tilde{\boldsymbol{A}}}{\partial t^2}-c^2\frac{\partial^2\tilde{\boldsymbol{A}}}{\partial z^2}-2\mathrm{i}\omega_0\frac{\partial\tilde{\boldsymbol{A}}}{\partial t}-2\mathrm{i}c^2k_0\frac{\partial\tilde{\boldsymbol{A}}}{\partial z}\\&\quad+\left[-\omega_0^2+k^2c^2+\omega_p^2P\exp\left(-\frac{\varGamma|\bar{\boldsymbol{A}}|^2(1-\alpha\sigma)}{2(1-\alpha\delta(\cos\theta+\sin\theta))^2}\right)\right]\tilde{\boldsymbol{A}}=0,\end{aligned} \tag{2.22}$$

in which the second term is related to the nonlinear dispersion relation. It is obvious that in this relation if the interaction between the plasma and the electromagnetic wave was ignored, then

$$\begin{aligned}D_{NL}&=\left(\frac{\omega_p^2}{\omega_0}\times\frac{1}{2(1-\alpha\sigma(\cos\theta+\sin\theta))}\right.\\&\quad\left.\times\left(1-\left(1-\frac{|\bar{\boldsymbol{A}}|^2}{2(1-\alpha\sigma)^2}\right)\exp\left(-\frac{\varGamma|\bar{\boldsymbol{A}}|^2(1-\alpha\sigma)}{2(1-\alpha\sigma(\cos\theta+\sin\theta))^2}\right)\right)\right),\end{aligned} \tag{2.23}$$

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where D_{NL} is the nonlinear dispersion relation for a hot magnetized plasma. In linear limit (2.23) decreases and it leads to a linear dispersion relation for right- and left-handed circularly polarized electromagnetic waves in a magnetized plasma according to (Krall, Trivelpiece & Gross 1973),

$$k_0 = \frac{\omega_0}{c}\left(1 - \frac{\omega_p^2}{\omega_0(\omega_0 - \sigma\omega_c(\cos\theta + \sin\theta))}\right)^{1/2}. \tag{2.24}$$

Neglecting the higher-order diffraction effects in (2.22) and expanding the nonlinear terms with respect to the normalized vector potential amplitude, the paraxial wave equation can be found as,

$$\left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right)\psi(r, z) = k_p^2\left[\frac{c^2}{\omega_p^2}\left(k_0^2 - \frac{\omega_0^2}{c^2}\right) + \frac{\omega_0}{(\omega_0 - \sigma\omega_c(\cos\theta + \sin\theta))} - |\psi|^2 H\right] \times \psi(r, z) = 0, \tag{2.25}$$

where $\psi = e\tilde{A}/m_{0e}c^2$ is the normalized amplitude of the vector potential and $k_p^2 = 4\pi n_e e^2/m_e c^2$. Moreover the nonlinear term is expressed as

$$H = \frac{\omega_0^4}{2(\omega_0 - \sigma\omega_c(\cos\theta + \sin\theta))^4} + \frac{\omega_0^2\beta_e}{2(\omega_0 - \sigma\omega_c(\cos\theta + \sin\theta))^2(1 + \eta)}. \tag{2.26}$$

The first term in (2.26), with $\theta = 0$ for a cold magnetized plasma, was already obtained by Jha *et al.* (2007), but for a hot magnetized plasma, the above relation is modified and has extra terms so that the second term of H is the thermal correction which is associated with the electron and ion temperatures in the presence of left- and right-handed polarizations, laser frequency and external magnetic field. The obtained result in this part is in implicit agreement with the results reported by Ghorbanalilu for a circularly polarized intense laser beam propagated through axially magnetized electron–positron (EP) and electron plasmas with $\theta = 0$ (Ghorbanalilu 2012).

3. The spot-size analysis of the laser beam

In order to analyse of laser spot size using the SDE method (Esarey *et al.* 1997) for self-focusing of an electromagnetic wave, the laser field amplitude can be expanded as a series of Laguerre–Gaussian modes as

$$\psi(r, z) = \sum_m \hat{\psi}_m L_m(\chi)\exp\left(\frac{-(1 - i\alpha_s)\chi}{2}\right) \quad \text{with } m = 0, 1, 2, 3, \ldots, \tag{3.1}$$

where $\hat{\psi}_m$ is the complex amplitude, $\chi = 2r^2/r_s^2$, r_s is the spot size, $\alpha_s(z) = kr_s^2/2R_c$ is associated with the curvature R_c that is the radius of curvature related to the wave front and $L_m(\chi)$ denotes a Laguerre polynomial of order m. Due to the fact that the higher-order SDE modes are small in comparison with the fundamental mode $m = 0$, the lowest-order mode of the Gaussian in (3.2) is considered. In addition, the amplitude of this mode is assumed to be $\hat{\psi}_0 = \psi_s \exp(i\theta_s)$, where ψ_s is the real amplitude and θ_s is phase (Jha *et al.* 2007). By using a series of Laguerre–Gaussian modes and inserting into (2.24) we have

$$\frac{\partial^2 r_s}{\partial z^2} = \frac{4}{k_0^2 r_s^3}\left(1 - \frac{k_p^2\psi_0^2 r_0^2 H}{8}\right). \tag{3.2}$$

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Here r_0 is the beam waist. The first term on the right-hand side of the above equation is the indicant vacuum diffraction and the second term is associated with the nonlinear effects of density perturbation, relativistic mass correction and magnetic field on the expansion of the laser spot size. The solution of differential equation (3.2) leads to

$$\frac{r_s^2}{r_0^2} = 1 + \left(1 - \frac{P}{P_c}\right)\frac{Z^2}{Z_R^2} \tag{3.3}$$

$$\frac{P}{P_c} = \frac{k_p^2 \psi_0^2 r_0^2}{8}\left[\frac{\omega_0^4}{2(\omega_0 - \sigma\omega_c(\cos\theta + \sin\theta))^4} + \frac{\omega_0^2 \beta_e}{2(\omega_0 - \sigma\omega_c(\cos\theta + \sin\theta))^2(1+\eta)}\right], \tag{3.4}$$

where P/P_c is the normalized power, $P_c = 2\pi^2 c^5 m_{0e}^2/k_p^2 \lambda^2 e^2 H$ is the critical power and $Z_R = k_0 r_0^2/2$ denotes the Rayleigh length. It must be mentioned that, in the absence of the magnetic field ($\omega_0 \to 0$), equation (3.3) decreases and yields the spot size for a laser beam propagated in an unmagnetized plasma (Esarey *et al.* 1997).

By substituting (3.4) into (3.3), we obtain,

$$n_e = \frac{2c^2 m_{0e}}{\pi e^2 \psi_0^2 r_0^2 \left(\dfrac{\omega_0^4}{2(\omega_0 - \sigma\omega_c(\cos\theta + \sin\theta))^4} + \dfrac{\omega_0^2 \beta_e}{2(\omega_0 - \sigma\omega_c(\cos\theta + \sin\theta))^2(1+\eta)}\right)} \times \left[\left(1 - \frac{r_s^2}{r_0^2}\right)\frac{Z_R^2}{Z^2} + 1\right]. \tag{3.5}$$

The above equation stands for the plasma density for nonlinear self-focusing of electromagnetic waves in a magnetized hot plasma in the presence of an oblique magnetized field.

4. Numerical results and discussion

In this section, a numerical study of the analysis of laser spot size has been made. We assume a Nd:YaG laser with frequency $\omega_0 = 1.88 \times 10^{15}\ \text{s}^{-1}$, intensity $I \approx 10^{17}\ \text{W cm}^{-2}$ ($\psi_0 = 0.271$) and the beam waist $r_0 = 15\ \mu\text{m}$. Also, the plasma frequency is considered to be a function of the physical parameter $\omega_p = 0.1\omega_0$.

Figure 1 shows the plasma density distribution of a hot magnetized plasma with respect to the variation of the normalized laser spot size r_s/r_0 at $T_e = 5$ keV for the right-handed polarization with $\theta = 0°$, $60°$, $120°$ and $180°$ when $\eta = T_e/T_i = 10$. It can be found that, for the right-handed polarization, when θ in the oblique magnetic field increases, the plasma density increases. Consequently, the laser spot size increases and the laser beam becomes more de-focused. Furthermore, the effect of the oblique magnetic field on the plasma density in right-handed polarization is profound.

From figure 2, it appears that, in contrast to figure 1, for the left-handed polarization, when θ in the oblique magnetic field increases, the plasma density reduces. As a result, the laser spot size reduces and the laser beam becomes more focused. Subsequently, the plasma density is decreased. Besides, the effect of an oblique magnetic field on the plasma density in left-handed polarization is more outstanding moreover, in figures 1 and 2 are appear. As shown in these graphs, self-focusing of the laser pulse along the shown in these graphs, self-focusing of the laser pulse along the propagation direction in a hot magnetized plasma becomes better and more compressed with increasing θ. In other words, in the density profile, the self-focusing of the laser pulse reduces in

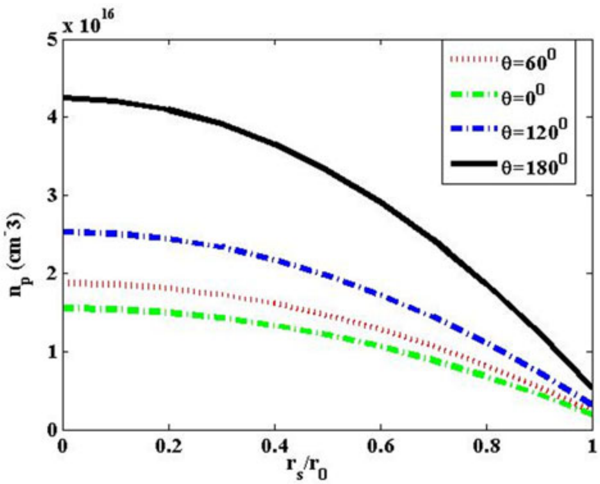

FIGURE 1. Plasma density distribution of a hot magnetized plasma with respect to the variation of the normalized laser spot size r_s/r_0 at $T_e = 5$ keV for right-handed polarization with $(\theta = 0^\circ, 60^\circ, 120^\circ, 180^\circ)$ when $\eta = T_e/T_i = 10$.

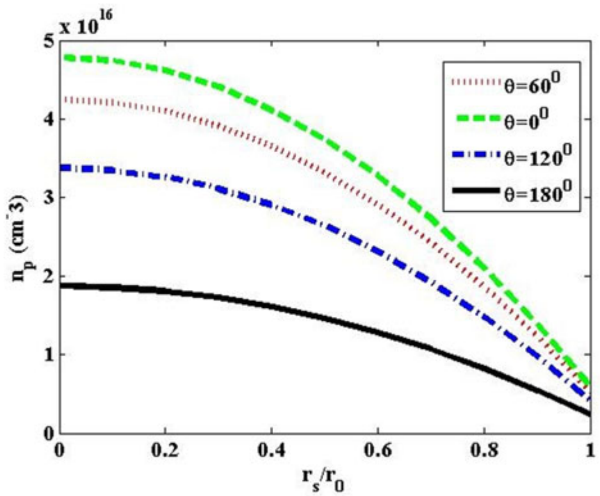

FIGURE 2. Plasma density distribution of a hot magnetized plasma with respect to the variation of the normalized laser spot size r_s/r_0 at $T_e = 5$ keV for the left-handed polarization with $(\theta = 0^\circ, 60^\circ, 120^\circ, 180^\circ)$ when $\eta = T_e/T_i = 10$.

comparison with that observed what a oblique magnetic field is employed. In fact, the oblique magnetic field has a significant role in the prevention of laser pulse defocusing.

Figure 3(a) demonstrates the variation of the normalized laser spot size with respect to the variation of the normalized propagation distance for the right-handed polarization with $\theta = 0^\circ$, 60°, 120°, 180° when $\eta = T_e/T_i = 10$ and the electron temperature is $T_e = 5$ keV. As can be seen from figure 3(a), in the right-handed polarization case the laser spot size reduces with increasing θ in an oblique magnetic

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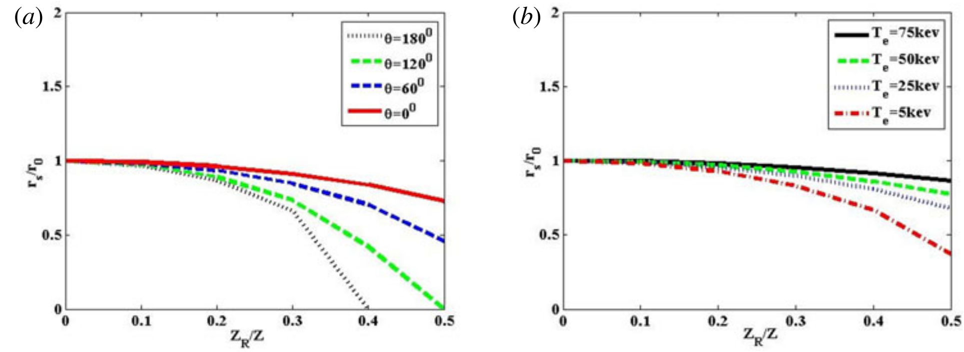

FIGURE 3. Variation of normalized laser spot size r_s/r_0 with respect to variation of the normalized propagation distance Z/Z_R for the right-handed polarization (*a*) at $T_e = 5$ keV with ($\theta = 0°, 60°, 120°, 180°$) and (*b*) with $\theta = 60°$ at $T_e = 5, 25, 50, 75$ keV.

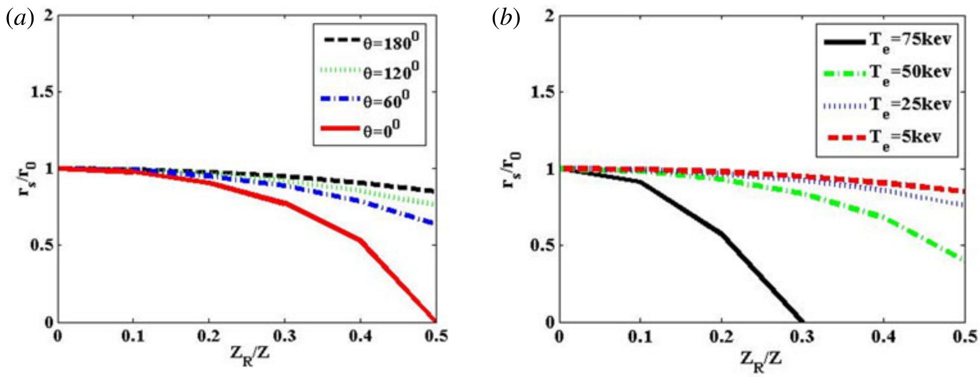

FIGURE 4. Variation of normalized laser spot size r_s/r_0 with respect to the variation of the normalized propagation distance Z/Z_R for the left-handed polarization (*a*) at $T_e = 5$ keV with ($\theta = 0°, 60°, 120°, 180°$) and (*b*) with $\theta = 60°$ at $T_e = 5, 25, 50, 75$ keV.

field and the laser beam becomes more focused. Moreover, as seen in figure 3(*b*), the self-focusing in the presence of an oblique magnetic field with decreasing plasma temperatures for the right-handed polarization increases. It is found that, in the right-handed polarization case, increase of θ in an oblique magnetic field and decrease in the plasma temperature lead to enhancement of the quality the self-focusing. As is clear from the figures, in the presence of an oblique magnetic field, the laser spot size reduces and consequently the self-focusing is enhanced relative to the state in which an external oblique magnetic field is not used. As a result, by increasing θ in an oblique magnetic field, the laser pulse self-focusing improves.

From figure 4 we find that the plasma temperature plays an effective role in determining the propagation properties of the laser beam. As shown in these figures, when we employ an external oblique magnetic field appropriately, self-focusing of the laser pulse in a hot magnetized plasma improves. Indeed, in the left-handed polarization case, an increase of θ in an oblique magnetic field and a decrease of temperature cause enhancement of de-focusing and a reduction of self-focusing. It is observed that when the electron temperature increases, the laser beam is more focused.

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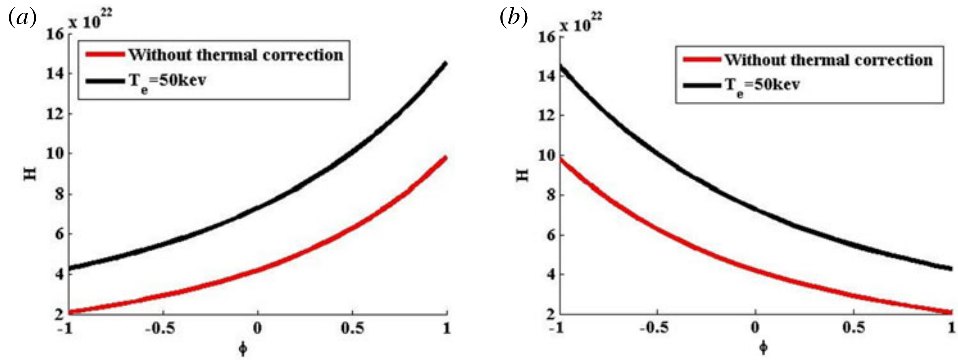

FIGURE 5. Variation of the nonlinear term of the wave equation with respect to the variation of $\Phi = \sin\theta + \cos\theta$ based on (2.26) for (*a*) the right-handed polarization and (*b*) the left-handed polarization. Black lines are for electron temperature $T_e = 50$ keV and red lines are for the case that where the thermal correction is neglected.

Figure 5 illustrates variation of the nonlinear term of the wave equation with respect to the variation of the Φ parameter for right- and left-handed laser polarization when $\eta = T_e/T_i = 10$ and the electron temperature is $T_e = 5$ keV, both with and without the thermal correction. It is obvious that for right- and left-handed polarizations, adding the thermal correction leads to variations in the nonlinear term of the wave equation. In the right-handed polarization case, when the nonlinear term of the wave equation increases, the Φ parameter increases. As a result, the laser spot size is enhanced and the laser pulse becomes more de-focused. It is apparent in figure 5(*b*) that for the left-handed polarization case, when the Φ parameter increases, the nonlinear term of the wave equation reduces. In addition, the role of temperature in de-focusing of a hot magnetized plasma ($T_e = 5$ keV) in the presence of an oblique magnetic field with and without consideration of the thermal correction is more significant.

Figure 6 shows the variation of the normalized laser power with respect to the variation of $\Phi = \sin\theta + \cos\theta$ at $T_e = 5, 25, 50, 75$ keV. It seems that the normalized laser power has an increasing trend with increasing Φ. With increasing plasma temperature, the variation of the power against initial laser frequency has a decreasing trend.

According to this figure, it is found that the temperature and Φ parameter have considerable effects on the normalized laser power in hot magnetized plasmas.

5. Conclusions

In summary, in this paper self-focusing and the laser spot size of an intense circularly polarized laser pulse in a hot magnetized plasma were investigated by employing an external oblique magnetic field. It was found that for the right-handed polarization case, increase of θ in an oblique magnetic field and a decrease in plasma temperature lead to enhancement of the quality of self-focusing and for left-handed polarization, increase de-focusing. In addition, in the plasma density profile, in the right-handed polarization case, when θ in an oblique magnetic field increases, the laser spot size increases and the laser beam becomes more de-focused and the plasma density is increased. The effect of plasma temperature on the self-focusing quality for left-handed polarization is more profound. Also, it was seen that for right-handed

https://doi.org/10.1017/S0022377817000460 Published online by Cambridge University Press

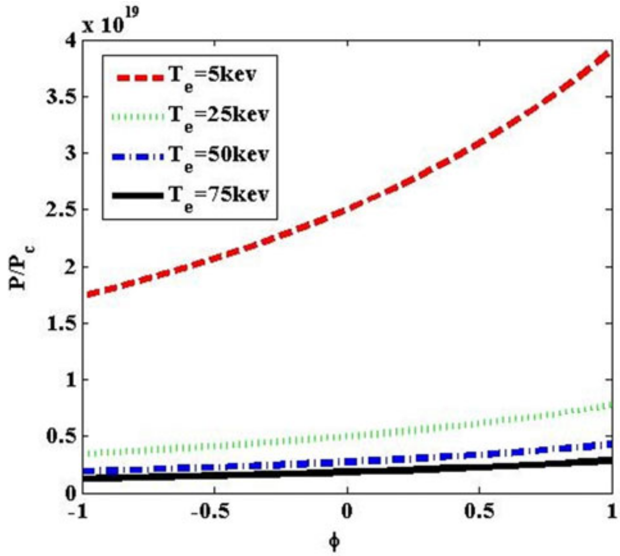

FIGURE 6. Variation of the normalized laser power with respect to variation of $\Phi = \sin\theta + \cos\theta$ at $T_e = 5, 25, 50, 75$ keV.

polarization, enhancement of temperature leads to de-focusing of the laser pulse and for left-handed polarization, a reduction of temperature causes a decrease of the spot size of laser pulse and an increase of self-focusing. Furthermore, the effect of plasma temperature on the variation of the normalized laser power with respect to a variation of the Φ parameter was studied. It was found that the temperature is a key factor in variation of the normalized laser power.

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