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Relativistic longitudinal self-compression of ultra-intense Gaussian laser pulses in magnetized plasma

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Abstract

This article presents a preliminary study of the longitudinal self-compression of ultra-intense Gaussian laser pulse in a magnetized plasma, when relativistic nonlinearity is active. This study has been carried out in 1D geometry under a nonlinear Schrodinger equation and higher-order paraxial (nonparaxial) approximation. The nonlinear differential equations for self-compression and self-focusing have been derived and solved by the analytical and numerical methods. The dielectric function and the eikonal have been expanded up to the fourth power of r (radial distance). The effect of initial parameters, namely incident laser intensity, magnetic field, and initial pulse duration on the compression of a relativistic Gaussian laser pulse have been explored. The results are compared with paraxial-ray approximation. It is found that the compression of pulse and pulse intensity of the compressed pulse is significantly enhanced in the nonparaxial region. It is observed that the compression of the high-intensity laser pulse depends on the intensity of laser beam (a_0), magnetic field (ω_c), and initial pulse width (τ_0). The preliminary results show that the pulse is more compressed by increasing the values of a_0, ω_c, and τ_0.

Introduction

The interaction of high-intensity ($>10^{18}$ W/cm^2) and ultrashort lasers (in order of femtosecond) with plasmas is a subject of great research interest for fundamental research and technological applications. These applications include particle acceleration, inertial confinement fusion, new radiation sources, and many more where laser–plasma interaction takes place (Tabak *et al.*, 1994; Bingham *et al.*, 2004; Malka, 2010; Liao *et al.*, 2017; Pape *et al.*, 2019). When such high-intensity ultrashort laser pulses propagate through the plasma, variety of interesting nonlinear effects such as self-focusing, filamentation, self-compression, harmonic generation, and stimulated Raman and Brillouin scattering have been observed (Ren *et al.*, 2001; Faisal *et al.*, 2008; Karle and Spatschek, 2008; Schroeder *et al.*, 2011; Purohit *et al.*, 2012; Purohit and Gaur, 2019). Self-compression and self-focusing of laser pulses are most important among them. The instantaneous intensity of the laser pulse become enhance many folds at the focused position due to these nonlinear effects. Chirped pulse amplification (CPA) technique (Strickland and Mourou, 1985; Mourou *et al.*, 2008) is used to produce an ultrashort, ultra-intense multi-terawatt laser pulse, in which the laser pulse is stretched, amplified, and recompressed by passing through a pair of the parallel diffraction grating. This technique can be used to generate ultrashort laser pulses up to 30 fs pulse durations. But the CPA technique is limited by the finite bandwidth of the active millimeter amplifiers used in lasers (Stuart *et al.*, 1996; Gamaly *et al.*, 2002). Medium plays a very important role in the compression of laser pulse because the propagation characteristics of laser pulses depend on the nonlinear response of the medium. Plasma offers a promising medium for self-compression of laser beam because this medium has no thermal damage threshold and can sustain extremely high intensities.

When the intensity of laser pulse reaches 10^{18} W/cm^2, electrons swing in the laser pulse with relativistic energies and the interaction between laser and plasma becomes highly nonlinear. The strong electric field associated with high-power laser pulses leads to a quiver motion of electrons is relativistic, that is, the drift velocity of electrons in a plasma of the order of the velocity of light. Since the relativistic mass variation of electrons is the origin of longitudinal self-compression of a laser pulse in laser–plasma interaction, thus pulse compression is dynamically correlated through the change in the pulse intensity (Sharma and Kourakis, 2010). The dielectric constant of the plasma is increased due to the relativistic mass increase of the oscillating electrons which leads to the dependence of the refractive index on the intensity.

The self-compression of short laser pulses in plasmas have been investigated in different situations. Due to the interplay between the self-phase modulations (due to the nonlinearity) and group velocity dispersion, the self-compression of laser pulse occurs in the plasma (Mora and Antonsen, 1997; Chessa *et al.*, 1998; Hauri *et al.*, 2004). Shorokhov *et al.* (2003) have studied the self-compression of weakly relativistic intense laser pulses in subcritical plasmas using one- (1D) and three-dimensional (3D) direct particle-in-cell (PIC) simulations. Their results revealed that a 30 fs pulse can be compressed to 5 fs in 3D PIC simulations. Sharma and Kourakis (2010) have investigated the self-compression of relativistic Gaussian laser pulse propagating in nonuniform plasma with an axial inhomogeneity. They have examined both longitudinal and transverse self-compression relativistic laser pulse in plasma. Their results showed that a significant enhancement of relativistic pulse compression in an axially inhomogeneous plasma, that is, 100 fs pulse is compressed in an inhomogeneous plasma medium by more than ten times. Olumi and Maraghechi (2014) have developed a theoretical model for longitudinal pulse compression of the relativistic Gaussian laser pulse in a magnetized plasma and shown that the laser pulse is compressed and amplified in an enhanced manner. They also observed that a negative initial chirp leads to an enhancement in the compression of the pulse with compared to the unchirped pulse and a positive initial chirp decompresses the pulse. Bokaei *et al.* (2015) have studied the spatio-temporal evolution of ultrahigh-intensity laser pulses in relativistic magnetized inhomogeneous plasmas. They have shown that the magnetic field and density ramp-up lead to generate pulses with the smallest spot size and the shortest compression length. Liang *et al.* (2015) have investigated the self-compression of a weak relativistic Gaussian laser pulse in a magnetized plasma. They observed the pulse compression in the cases of left- and right-hand circular polarized laser fields and found that a 100 fs left-hand circular laser pulse is compressed in a magnetized plasma by more than ten times. Gupta *et al.* (2016) have investigated the simultaneous compression of the laser pulse in temporal as well as in spatial domains during propagation in plasma having relativistic nonlinearity. They showed that pulse duration shortens to less than 5 fs and 11 times intensity enhancement. Saedjalil and Jafari (2016) have studied the effects of the external tapered axial magnetic field and plasma density-ramp on the spatio-temporal evolution of the laser pulse in inhomogeneous plasma and observed that self-focusing and self-compression are better enhanced in a tapered magnetic field than in a uniform one. Kumar *et al.* (2017) have investigated the combined effect of relativistic and ponderomotive nonlinearities on pulse compression and self-focusing of Gaussian laser pulses in plasma. Cao *et al.* (2017) have investigated the spatio-temporal evolution of the ultrashort time-domain dark hollow Gaussian (TDHG) pulses in homogeneous plasma and found that the intensity of the TDHG pulses increases mostly by one order of magnitude compared to the initial time. Singh and Gupta (2018) have investigated the impact of light absorption on the longitudinal pulse compression under Ohmic and weak-relativistic ponderomotive nonlinearity in plasmas. They found that the absorption overcomes the effect of self-compression and the beam becomes too weak to control the dispersion broadening. The other studies of self-compression of the laser pulse in plasma have been found in the literature (Shibu *et al.*, 1998; Lontano and Murusidze, 2003; Balakin *et al.*, 2012; Bokaei and Niknam, 2014; Shi *et al.*, 2017; Wilson *et al.*, 2019).

Most of these studies have been carried out under paraxial-ray approximation where the expansion of the eikonal and nonlinear dielectric constant taken up to square term r^2, where r is the distance from the axis of beam. However, this theory is not applicable when high-power laser beams are used (Subbarao *et al.*, 1998) because this theory predicts the unphysical phase relationship (Karlsson *et al.*, 1991). When the initial intensity of the laser beam is larger than the threshold, then this approximation fails after some distance of propagation. Another global approach is nonparaxial-ray approximation (Sodha and Faisal, 2008; Gill *et al.*, 2010), where eikonal and other relevant quantities become expanded up to fourth power of r. A survey of the literature reveals that the self-compression of an intense laser beam in plasma under nonparaxial-ray approximation has not been studied so far. Moreover, when the intensity of laser pulse reaches $10^{18}\,\mathrm{W/cm^2}$, electrons swing in the laser pulse with relativistic energies and the interaction between laser and plasma becomes highly nonlinear. The strong electric field associated with high-power laser pulses leads to a quiver motion of electrons is relativistic, that is, the drift velocity of electrons in a plasma of the order of the velocity of light. The dielectric constant of the plasma is increased due to a relativistic mass increase of the oscillating electrons which leads to the dependence of the refractive index on the intensity. Therefore, the relativistic variation of mass of the electrons is mainly the origin of longitudinal self-compression of a laser pulse in plasma.

In this article, we have investigated the longitudinal self-compression of an intense laser pulse in a magnetized plasma under nonparaxial-ray theory, when relativistic nonlinearity is operative. The effects of incident laser intensity, magnetic field, and pulse duration on pulse compression of the laser beam have been numerically investigated. The results are compared with paraxial-ray approximation. Results clearly distinguish the difference between paraxial- and nonparaxial-ray approximations. In the "Analytical formulation for longitudinal self-compression" section, we have given a brief description of the pulse compression of the relativistic laser beam in a magnetized plasma. The equations for pulse width and pulse intensity have been derived from the nonlinear Schrodinger equation under nonparaxial approximation. The expression for the nonlinear dielectric constant of the plasma in the presence of relativistic nonlinearity is also given in this section. A detailed discussion of the numerical results carried out for the relevant parameters is given in the "Numerical results and discussion" section. The conclusions of the present investigation are presented in the last section.

Analytical formulation for longitudinal self-compression

We consider the propagation of a relativistic laser pulse in the uniform density magnetized plasma (n_0) in the z-direction. The electric field of such laser pulse can be expressed as follows:

$$E_0(z, t) = \hat{x}A_0(z, t)\exp[-i(\omega_0 t - k_0 z) \qquad (1)$$

where ω_0 is the frequency of the incident laser pulse, $k_0(= \omega_0\varepsilon_0^{1/2}/c)$ is the wavenumber, $\varepsilon_0(= 1 - (\omega_{p0}^2/\omega_0^2))$ is the dielectric function on the axis of the pulse, and $\omega_{p0}(= 4\pi\, n_0 e^2/m_0)$ is the electron plasma frequency. The intensity of an initial

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Gaussian laser pulse at $z = 0$ is given by

$$A_0^2|_{z=0} = A_{00}^2 \exp\left(\frac{-t^2}{\tau_0^2}\right) \tag{2}$$

where τ_0 is the initial pulse width.

When transverse variations are neglected, the electric field of the laser pulse satisfies the following wave equation in one-dimensional (Olumi and Maraghechi, 2014):

$$\frac{\partial^2 E_0}{\partial z^2} - \frac{\varepsilon}{c^2}\frac{\partial^2 E_0}{\partial t^2} = 0 \tag{3}$$

where ε is the effective dielectric constant, and in the relativistic magnetized plasma, it can be expressed as follows (Gill *et al.*, 2010):

$$\varepsilon = 1 - \frac{\omega_{p0}^2}{[\omega_0 - (\omega_{ce}/\gamma_0)]} \tag{4}$$

where $\omega_{ce}(= eB_0/m_0c)$ is the electron cyclotron frequency and B_0 is the external magnetic field. The relativistic factor (γ_0) is given by

$$\gamma_0 = \left[1 + a_0^2\left(1 - \frac{\omega_{ce}}{\gamma_0\omega_0}\right)^{-2}\right]^{\frac{1}{2}} \tag{5}$$

where

$a_0^2 = \alpha|A_0^2|$ with $(\alpha = e^2/m_0^2c^2\omega_0^2)$ is the incident intensity of the laser beam.

Equation (5) can be expanded as

$$\gamma_0 = \left[1 + a_0^2 + 2a_0^2\frac{\omega_{ce}}{\omega_0}\left(\frac{1}{(1+a_0^2)^{1/2}}\right) + 3a_0^2\left(\frac{\omega_{ce}}{\omega_0}\right)^2\left(\frac{1}{(1+a_0^2)}\right)\right]^{\frac{1}{2}} \tag{6}$$

In the nonparaxial approximation, the dielectric constant of plasma can be expressed as a series in t^2 and t^4 as

$$\varepsilon(z,t) = \varepsilon_0(z) - \frac{t^2}{\tau_0^2}\varepsilon_{2t}(z) - \varepsilon_{4t}(z)\frac{t^4}{\tau_0^4} \tag{7}$$

where

$$\varepsilon_0(z) = 1 - \frac{\omega_{p0}^2}{\omega_0^2}\alpha_0$$

$$\varepsilon_{2t}(z) = -\frac{\omega_{p0}^2}{\omega_0^2}\alpha_1\alpha_2$$

and

$$\varepsilon_{4t}(z) = \frac{\omega_{p0}^2}{\omega_0^2}(2\alpha_2^2\alpha_3 - \alpha_1\alpha_4)$$

with

$$\alpha_0 = 1 + \frac{\omega_{ce}}{\omega_0} + \frac{\omega_{ce}^2}{\omega_0^2} - \frac{a_0}{2}A^2 + \frac{a_0^2}{8}\left(3A^2 - 4B + 8\frac{\omega_{ce}}{\omega_0}(A^2 - B) + 3\frac{\omega_{ce}^2}{\omega_0^2}(5A^2 - 4B)\right) + \frac{a_0^3}{4}\left(3AB - 2C + 4\frac{\omega_{ce}}{\omega_0}(2AB - C) + 3\frac{\omega_{ce}^2}{\omega_0^2}(5AB - 2C)\right)$$

$$\alpha_1 = A - \frac{a_0}{2}A\left(1 + 6\frac{\omega_{ce}}{\omega_0} + 12\frac{\omega_{ce}^2}{\omega_0^2}\right) + \frac{a_0^2}{8}\left(3A^2 - 4B + 6\frac{\omega_{ce}}{\omega_0}(5A^2 - B) + 24\frac{\omega_c^2}{\omega_0^2}(3A^2 - 2B)\right) + \frac{a_0^3}{4}\left(3AB - 2C + 6\frac{\omega_{ce}}{\omega_0}(5AB - 2C) + 24\frac{\omega_{ce}^2}{\omega_0^2}(3AB - C)\right)$$

$$\alpha_2 = \frac{a_0}{2}\frac{A}{\tau_1^2 g^3}(a_2 - 1) + \frac{a_0^2}{4}\frac{(4B - A^2)}{\tau_1^2 g^4}(a_2 - 1) + \frac{a_0^3(AB + 2C)}{\tau_1^2 g^5}(a_2 - 1)$$

$$\alpha_3 = A - B - \frac{3a_0}{2}A\left(1 + 4\frac{\omega_{ce}}{\omega_0} + 10\frac{\omega_{ce}^2}{\omega_0^2}\right) + \frac{3a_0^2}{8}\left(5A^2 - 4B + 8\frac{\omega_{ce}}{\omega_0}(3A^2 - 2B) + 10\frac{\omega_{ce}^2}{\omega_0^2}(7A^2 - 4B)\right) + \frac{3a_0^3}{4}\left(5AB - 2C + 8\frac{\omega_{ce}}{\omega_0}(3AB - C) + 10\frac{\omega_{ce}^2}{\omega_0^2}(7AB - 2C)\right)$$

and

$$\alpha_4 = \frac{a_0}{2}\frac{A}{2\tau_1^4 g^5}(2a_4 - 2a_2 + 1) + \frac{a_0^2}{4}\frac{(4B - A^2)}{\tau_1^4 g^6}(2a_4 - 4a_2 + a_2^2 + 2) + \frac{a_0^3(AB + 2C)}{\tau_1^4 g^7}(2a_4 - 4a_2 + 3a_2^2 + 4)$$

where

$$A = 1 + 2\frac{\omega_{ce}}{\omega_0} + 3\frac{\omega_{ce}^2}{\omega_0^2}$$

$$B = -\frac{\omega_{ce}}{\omega_0} - 3\frac{\omega_{ce}^2}{\omega_0^2}$$

and

$$C = \frac{3}{4}\frac{\omega_{ce}}{\omega_0} + 3\frac{\omega_{ce}^2}{\omega_0^2}$$

Combining Eqs. (1) and (7) into the wave Eq. (3), one obtains

$$2ik_0\left(\frac{\partial A_0}{\partial z} + \frac{1}{v_g}\frac{\partial A_0}{\partial t}\right) - \frac{1}{c^2}\frac{\partial^2 A_0}{\partial t^2} + \frac{\partial^2 A_0}{\partial z^2} + \frac{k_0^2}{\varepsilon_0}(\varepsilon - \varepsilon_0)A_0 = 0 \tag{8}$$

where $\upsilon_g = c\varepsilon_0^{1/2}$ is the group velocity of the laser pulse. Now introducing a new set of variables, that is,

$$\xi = \omega_0 z/c, \quad \tau = (z/\upsilon_g - t)\omega_0, \quad a_0 = \frac{eA_0}{m_0\omega_0 c}, \quad \text{and} \quad \frac{\partial^2 A_0}{\partial z^2} \approx \frac{1}{\upsilon_g^2}\frac{\partial^2 A_0}{\partial t^2}$$

Equation (8) takes the form

$$2i\varepsilon_0^{1/2}\frac{\partial a_0}{\partial \xi} + \frac{\partial^2 a_0}{\partial \tau^2} + (\varepsilon - \varepsilon_0)a_0 = 0 \tag{9}$$

Equation (9) is the nonlinear Schrödinger wave equation, which describes the propagation of laser beam in plasma. The second term in Eq. (9) is known as a group velocity dispersion broadening term, while the third term represents the nonlinear self-compression. The coherent structure in the form of a solitary wave can be obtained when these two effects balance each other.

The solution of Eq. (9) can be written as

$$a_0(\xi, \tau) = a(\xi, \tau)\exp[ik_0 S(\xi, \tau)] \tag{10}$$

Using Eq. (10) into Eq. (9) and separating the real and imaginary parts, we get

$$2\frac{\partial S}{\partial \xi} + \frac{k_0}{\varepsilon_0^{1/2}}\left(\frac{\partial S}{\partial \tau}\right)^2 = \frac{1}{k_0\varepsilon_0^{1/2}a}\frac{\partial^2 a}{\partial \tau^2} - \frac{1}{k_0\varepsilon_0^{1/2}}\left[\frac{t^2}{\tau_0^2}\varepsilon_{2t}(\xi) + \varepsilon_{4t}(\xi)\frac{t^4}{\tau_0^4}\right] \tag{11}$$

and

$$\frac{\partial a^2}{\partial \xi} + \frac{k_0}{\varepsilon_0^{1/2}}\frac{\partial a^2}{\partial \tau}\frac{\partial S}{\partial \tau} + \frac{k_0}{\varepsilon_0^{1/2}}a^2\frac{\partial^2 S}{\partial \tau^2} = 0 \tag{12}$$

The solution of Eqs. (11) and (12) under higher-order paraxial theory can be written as follows (Sodha and Faisal, 2008; Gill *et al.*, 2010):

$$a^2(\xi, \tau) = \left(\frac{a_{00}^2}{g}\right)\left(1 + \frac{\tau^2}{\tau_1^2 g^2}a_2 + \frac{\tau^4}{\tau_1^4 g^4}a_4\right)\exp\left(-\frac{\tau^2}{\tau_1^2 g^2}\right) \tag{13}$$

and

$$S(\xi, \tau) = S_0(\xi) + \frac{\tau^2}{\tau_0^2}S_2(\xi) + \frac{\tau^4}{\tau_0^4}S_4(\xi) \tag{14}$$

where a_2 and a_4 are the contributions from the τ^2, τ^4 coefficients and are functions of (τ, ξ), a_{00} is the normalized laser strength, $g = g(z)$ is the dimensionless pulse compression parameter in the longitudinal direction, and $\tau_1 = \tau_0\omega$ is the initial dimensionless pulse width (in time), and

$$S_2 = \frac{\tau_0^2}{k_0}\frac{\varepsilon_0^{1/2}}{2g}\frac{\partial g}{\partial \xi} \tag{15}$$

The parameters S_0, S_2, and S_4 are the components of the eikonal contributions from τ^2 and τ^4 coefficients in the nonparaxial region. Parameters S_2 and S_4 are indicative of the spherical curvature of the wave front and its departure from the spherical nature, respectively. The parameters a_2 and a_4 are indicative of the departure of the beam from the Gaussian nature.

Substituting a^2 and $S(\xi, \tau)$ from Eqs. (13) and (14) into Eqs. (11) and (12) and equating the coefficients of τ^0, τ^2, and τ^4 in the resulting equation on both sides of resulting equations, we obtained the following equation for g, S_4 a_2, and a_4:

$$\varepsilon_0\frac{\partial^2 g}{\partial \xi^2} = \frac{(6a_4 - 2a_2^2 - 2a_2 + 1)}{\tau_1^4 g^3} - \varepsilon_{2t}g \tag{16}$$

$$\frac{1}{\tau_0^4}\frac{\partial S_4'}{\partial \xi} = \frac{(9a_2^3 - 22a_2a_4 - 8a_4 + 4a_2^2)}{4\varepsilon_0\tau_1^6 g^6} - \frac{\varepsilon_{4t}}{2\varepsilon_0} \tag{17}$$

$$\frac{\partial a_2}{\partial \xi} = -16S_4' g^2 \tag{18}$$

$$\frac{\partial a_4}{\partial \xi} = -8S_4' g^2(1 - 3a_2) \tag{19}$$

where

$$S_4' = S_4\frac{\omega_0}{c}$$

Equation (17) shows the components of the eikonal contributions from τ^2 and τ^4 coefficients in the nonparaxial region. Eliminating S_4' from Eqs. (18) and (19) and integrating the resulting equation with the initial conditions $a_2 = 0$ and $a_4 = 0$ at $\xi = 0$, we obtain

$$a_4 = \frac{(3a_2^2 - 2a_2)}{4} \tag{20}$$

In the paraxial case, $a_2 = a_4 = 0$, while in the nonparaxial case, $a_2 \neq a_4 \neq 0$.

Equation (16) describes the longitudinal self-compression of a laser pulse in a magnetized plasma, that is, governing the behavior of the dimensionless pulse compression parameter (g) as a function of propagation distance.

Numerical results and discussion

When an intense Gaussian laser pulse propagates through the plasma, the dielectric constant gets modified due to the relativistic nonlinearity which leads to the self-compression of the laser pulse in the plasma. We have solved Eq. (18) numerically to investigate self-compression of the relativistic laser pulse in a magnetized plasma. The first term in the right-hand side of Eq.(16) represents the dispersion of laser pulse, which is responsible for the decompression of pulse; while the second term arises due to the combined effect of relativistic nonlinearity and the magnetic field. The relative magnitude of these terms determines the self-compression of laser pulse in the plasma. When the magnitude of the second term on the right-hand side of Eq. (16) becomes larger than the first term, self-compression of the laser pulse occurs in the plasma. Equation (13) gives the intensity profile of the laser beam in the

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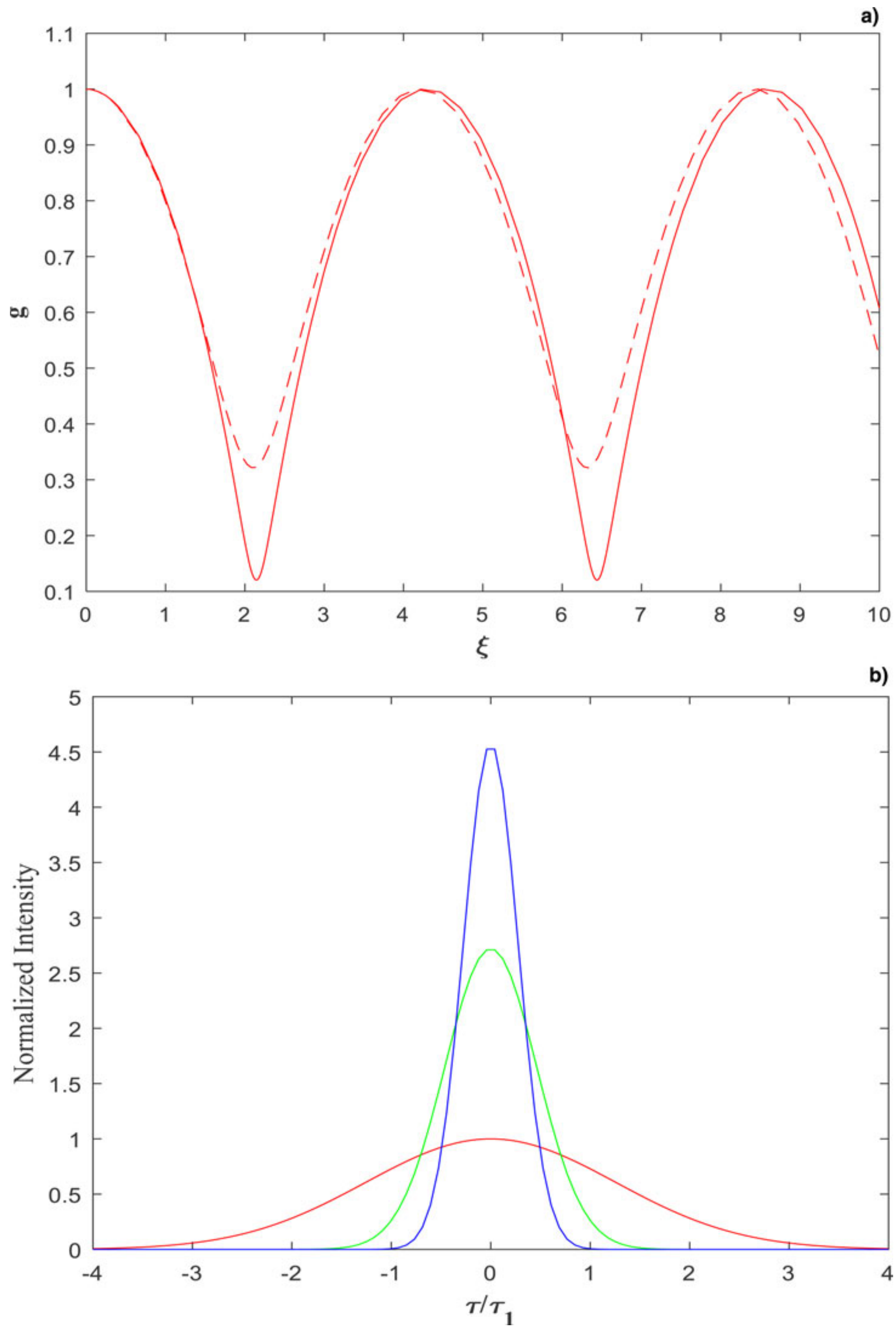

Fig. 1. (a) Variation of the pulse compression parameter (g) with the normalized propagation distance (ξ), when relativistic nonlinearity is operative in the nonparaxial and paraxial regions. Keeping $a = 3.5$, $\omega_{ce} = 0.3\omega_0$, and $\tau_0 = 100$ fs. Red solid and dotted lines are for the nonparaxial and paraxial regions, respectively. (b) Variation of the initial, and compressed laser pulse intensity with (τ/τ_1) in the nonparaxial and paraxial regions (2D). Keeping $a = 3.5$, $\omega_{ce} = 0.3\omega_0$, and $\tau_0 = 100$ fs. Red, green, and blue lines are for initial laser pulse, compressed laser pulse in the paraxial and nonparaxial regions, respectively.

plasma, when relativistic nonlinearity is operative. The intensity profile of the laser pulse depends on the pulse width parameters g and the coefficients a_2 and a_4 of τ^2 and τ^4 in the nonparaxial region. In order to investigate self-compression of a relativistic Gaussian laser pulse in a magnetized plasma in the nonparaxial region, the numerical computation of Eqs. (13)-(20) has been performed for the typical laser plasma parameters and the results are presented in the form of Figures 1 and 2. These parameters are:

$\omega_0 = 1.778 \times 10^{15}$ rad/s, $\omega_{p0} = 0.2\omega_0$, $n_0 = 3.97 \times 10^{17}$ cm^{-3}, $\tau_0 = 100$ fs, and $a = 3$, 3.5, and 4 corresponding to intensities 1.1 x 10^{19} Wcm^2 , 1.49×10^{19}W/cm^2 and 1.95×10^{19} W/cm^2, respectively. The boundary conditions for an initially plane wave front at $\xi = 0$ are $g = 1$ and $\delta g/\delta\, \xi = 0$.

Figure 1a shows the variation of the pulse compression parameter (g) with the normalized distance of propagation (ξ) in the nonparaxial and paraxial regions, when relativistic nonlinearity is operative. As the laser beam propagates through the plasma, it gets compressed due to the nonlinear effects. It is obvious that the pulse becomes more compressed in the nonparaxial region in comparison to the paraxial region due to the participation of the off-axis components a_2 and a_4. The intensity pattern of the initial pulse and the fully compressed pulse in the nonparaxial and paraxial regions is shown in Figure 1b. It is evident that the intensity of the compressed pulse is enhanced in the nonparaxial region. The intensity of a compressed pulse becomes increases in the nonparaxial region in comparison to the paraxial region due

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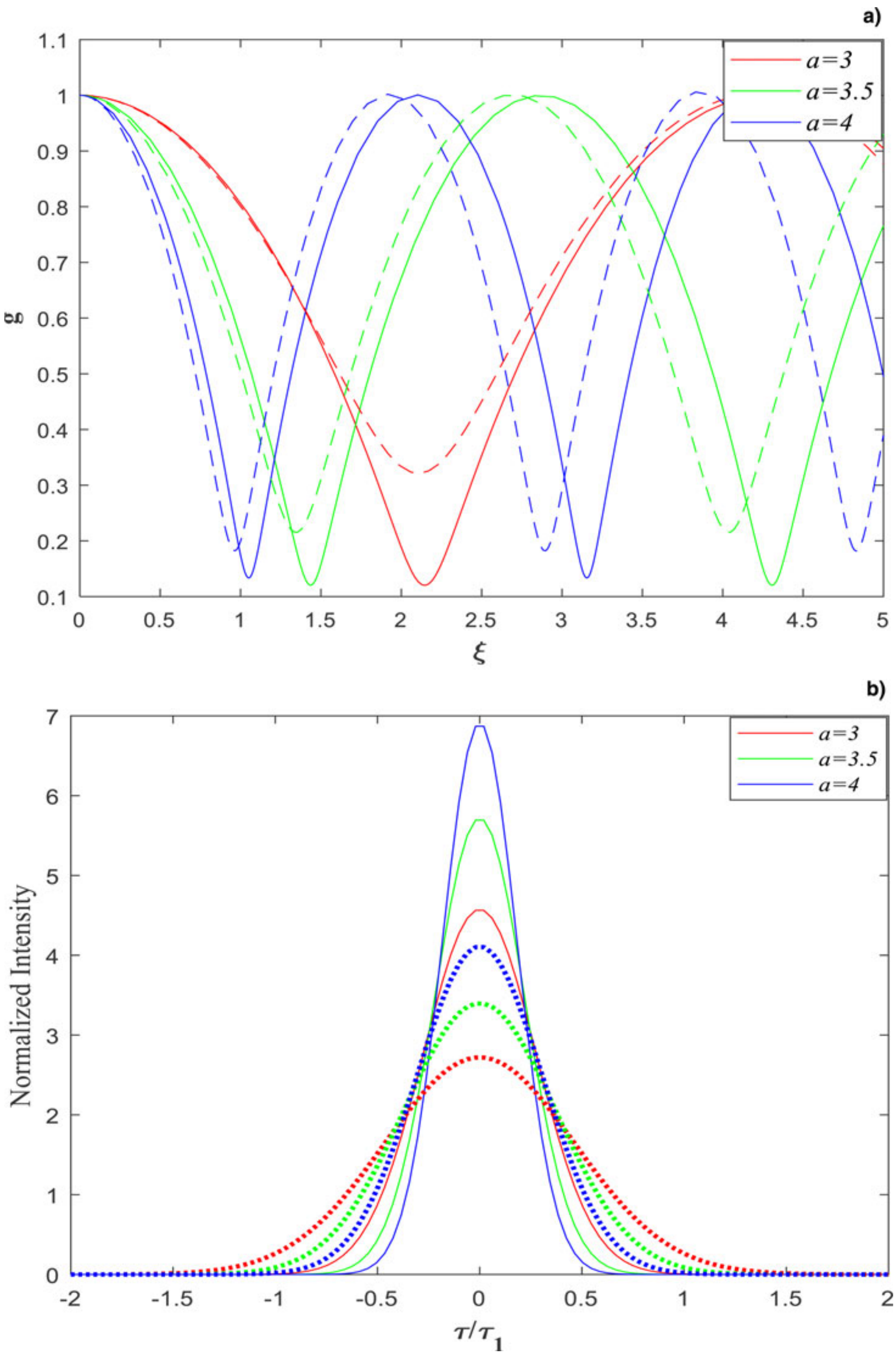

Fig. 2. (a) Variation of the pulse compression parameter (g) with the normalized propagation distance (ξ), when relativistic nonlinearity is operative in the nonparaxial and paraxial regions. Keeping ω_{ce} ($=0.3\omega_0$) and τ_0 (=100 fs) are constant, at different laser beam intensities. Solid and dotted lines are for the nonparaxial and paraxial regions, respectively. (b). Variation of compressed laser pulse intensity with (τ/τ_1) in the nonparaxial and paraxial regions (2D) for different values of laser beam intensities. Keeping $\omega_{ce} = 0.3\omega_0$ and $\tau_0 =$ 100 fs. Solid and dotted lines are for the nonparaxial and paraxial regions, respectively.

to the participation of the off-axis components (a_2 and a_4) of r^2 and r^4 as well as strong laser–plasma coupling in the nonparaxial region. The coupling becomes strong due to the contribution of the off-axial coefficients a_2 and a_4. The maximum intensity of a compressed pulse gets enhanced by a factor of nearly five, when relativistic nonlinearity is operative.

Figure 2a represents the variation of the pulse compression parameter (g) with the normalized distance of propagation (ξ) for different values of incident laser intensity in the nonparaxial and paraxial regions. In both regions, the laser beam is self-compressed and show an oscillatory behavior. It is obvious from Figure 2a that with the increase in the value of intensity parameter, the pulse compression parameter (g) decreases, that is, the rate of pulse compression increases. This is because the second term on the right-hand side of Eq. (16) dominates. It is found that the pulse is more compressed at higher values of incident laser intensity in the nonparaxial region. Figure 2b shows the intensity profile of compressed laser pulse in a magnetized plasma for different values of incident laser intensity in the nonparaxial and paraxial regions. It is clear from Figure 2b that the pulse intensity of compressed laser pulse increases with an increase in the values of the intensity parameter. The pulse intensity of

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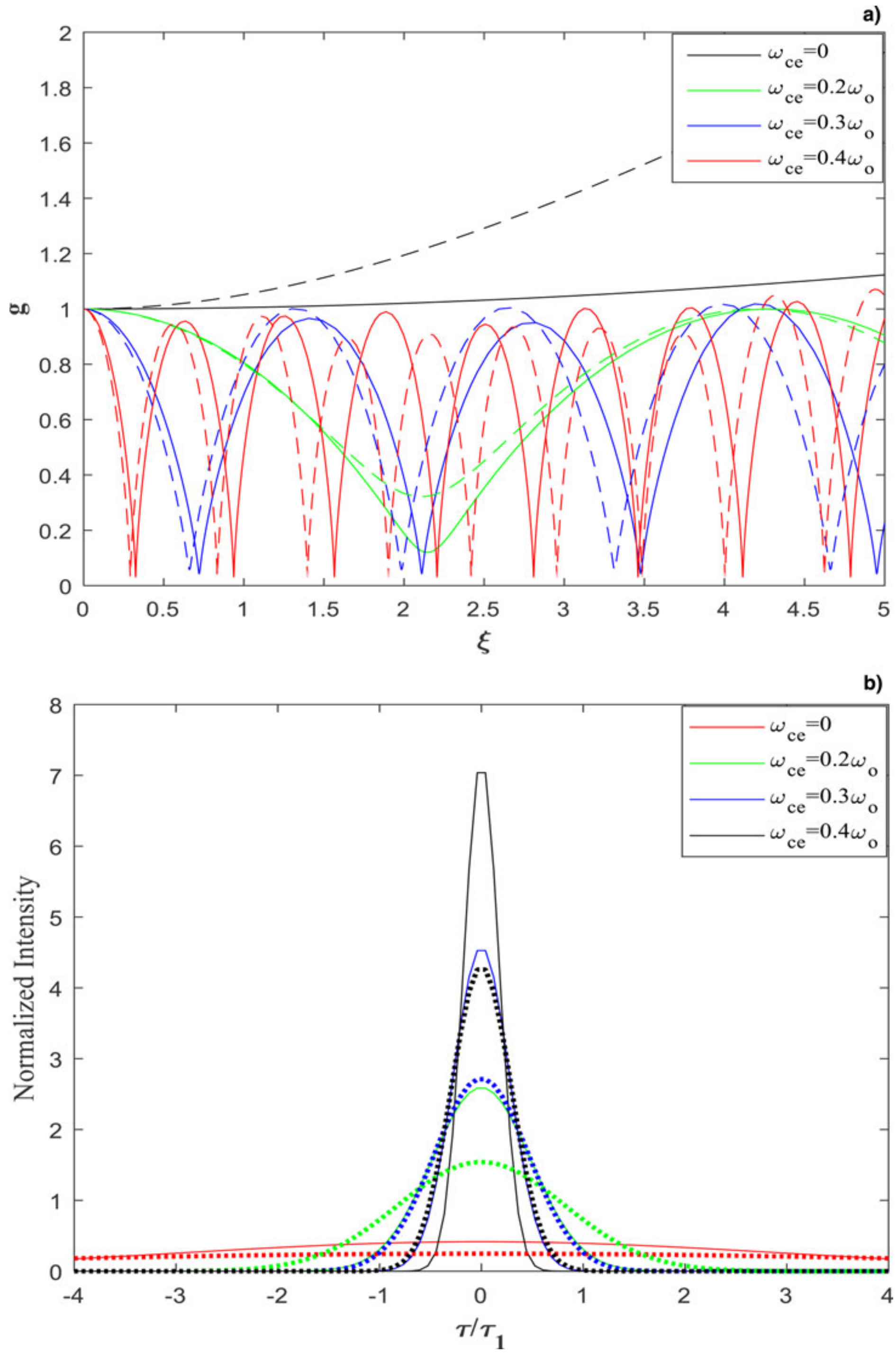

Fig. 3. (a) Variation of the pulse compression parameter (g) with the normalized propagation distance (ξ), when relativistic nonlinearity is operative in the nonparaxial and paraxial regions, keeping a (=3.5) and τ_0 (=100 fs) are constant, at different laser beam intensities. Solid and dotted lines are for the nonparaxial and paraxial regions, respectively. (b) Variation of the compressed laser pulse intensity with (τ/τ_1) in the nonparaxial and paraxial regions (2D) for different values of ω_{ce}, keeping a = 3.5 and τ_0 = 100 fs. Solid and dotted lines are for the nonparaxial and paraxial regions, respectively.

compressed laser pulse becomes also enhanced in the nonparaxial region in comparison to the paraxial case due to the participation of off-axis parts ($a_2 \neq a_4 = 0$).

Figure 3a displays the variation of the pulse compression parameter (g) with the normalized propagation distance (ξ) for different values of the magnetic field parameter (ω_c/ω_0), namely 0, 0.2. 0.3, and 0.4 in the nonparaxial and paraxial regions. It can be clearly observed that the pulse is not compressed when $\omega_c = 0$. The pulse becomes more compressed at higher values of the magnetic field in the nonparaxial region. Figure 3b depicts the time variation of the pulse intensity of the compressed relativistic laser pulse for different values of the magnetic field in the nonparaxial and paraxial regions. It can be seen that with the increase in the value of the magnetic field parameter (ω_c/ω_0), the pulse intensity increases and the pulse intensity becomes enhanced in the nonparaxial case in comparison to the paraxial case.

The effect of pulse duration (τ_0) on the pulse compression parameter (g) with the normalized propagation distance (ξ) in the nonparaxial and paraxial regions is illustrated in Figure 4a. It is evident from Figure 4a, as the value of τ_0 increases, the pulse becomes starts to broaden. The pulse is more compressed

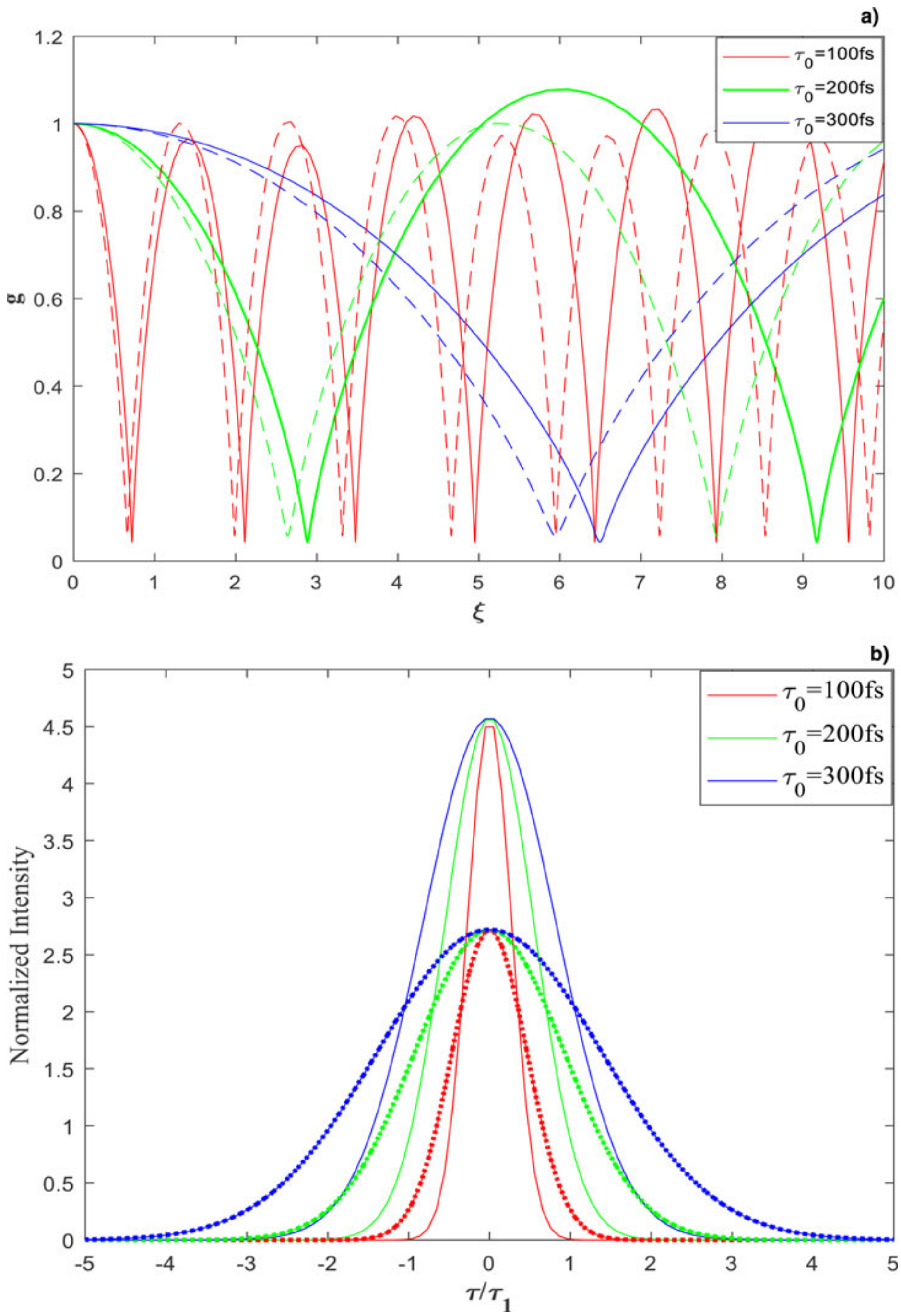

Fig. 4. (a) Variation of the pulse compression parameter (g) with the normalized propagation distance (ξ), when relativistic nonlinearity is operative in the nonparaxial and paraxial regions, keeping a (=3.5) and ω_{ce} (=0.3ω_0) are constant, at different values of pulse duration (τ_0). Solid and dotted lines are for the nonparaxial and paraxial regions, respectively. (b) Variation of the compressed laser pulse intensity with (τ/τ_1) in the nonparaxial and paraxial regions (2D) for different values of τ_0, keeping a = 3.5 and ω_{ce} = 0.3ω_0. Solid and dotted lines are for the nonparaxial and paraxial regions, respectively.

at a lower value of τ_0 (=100 fs) in both regions. Figure 4b shows the plot of the pulse intensity of the compressed laser pulse with time for different values of τ_0 in the nonparaxial and paraxial regions. It is obvious that for a higher value of τ_0, the pulse intensity is slightly increasing but the pulse intensity becomes more compressed at τ_0 (=100 fs) in both regions. In addition, the pulse intensity becomes more in the nonparaxial region due to the contribution of the off-axis components.

Conclusions

In the present investigation, the nonparaxial theory has been used to explain the phenomenon of self-compression of the intense short laser pulse (in the longitudinal direction) in a magnetized plasma in the presence of relativistic nonlinearity. The equations for the pulse width parameter and the pulse intensity has been derived using the nonparaxial approximation for the nonlinear Schrodinger equation. The results have been compared with paraxial-ray theory. It is found that the pulse becomes more compressed in the nonparaxial region. The intensity of the compressed pulse increases by more than two order of magnitude compared to the initial pulse. Moreover, we have explored the effect of various laser and plasma parameters, namely incident laser intensity (a), magnetic field (ω_{ce}), and pulse duration (τ/τ_1) on the compression of the laser pulse. It has been observed that pulse compression is highly sensitive to these parameters.

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The compression of laser pulse becomes enhanced by increasing the values of these parameters. It is also shown that the pulse intensity of the compressed pulse is increased with increasing the values of these parameters. These preliminary results describe a significant enhancement of relativistic pulse compression in a magnetized plasma and may be useful to generate high intensity and short duration pulses. Moreover, this study can be extended in 3D geometry which may give more realistic results. This work is under progress but is beyond the scope of the present study.

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