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Influence of Magnetic field and Decentred Parameter on Self-Focusing of Cosh-Gaussian Laser Beam in Collisional Magnetized Plasma

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Abstract

In the present investigation, Three-dimensional Cosh-Gaussian laser beam is introduced. The self-focusing and defocusing of Cosh-Gaussian laser beam in collisional magnetized plasma have been investigated theoretically. The final Differential equation for the beam width parameter is derived by following Wentzel-Kramer's-Brillouin (WKB) and paraxial approximation through standard Akhmanov`s parabolic wave equation. The final results of numerical computation are presented in the plot of beam width parameters (f1 & f2) versus normalized propagation distance ( ). In present investigation the author shows nonlinear effect due to magnetic field (B_0), decentered parameter (b) and plasma density on self-focusing and defocusing in collisional magnetized plasma. The results show well enhancement in beam of self-focusing.

Keywords: Self-Focusing, Cosh Gaussian Laser, Collisional Plasma.

Introduction

The nonlinear interaction of high intensity laser pulse with plasmas is attractive due to its relevance to laser wake-field acceleration, X-ray lasers, acceleration of charged particles, laser driven fusion, optical harmonic generation and fast igniters concept of inertial confinement fusion [1-10]. In all these applications need the laser beams to propagate over several Rayleigh lengths in the plasmas without loss of the energy as well as it is necessary to know the propagation characteristics of laser beam while getting an efficient interaction with plasma [11-12]. In a nonlinear medium like dielectrics, semiconductors and plasmas, the phenomenon of self-focusing being genuinely nonlinear optical process is induced by modification of refractive index of material to intense laser beam [13]. In collisional plasmas, the ponderomotive force of laser beam pushes the electrons outward from the axial region and modifies the distribution of electron density which is cause to change the refractive index of plasma which in turn to lead self-focussing of laser beam process [14]. To study self-focusing of laser beams most of researchers used Wentzel-Kramer-Brillion (WKB) and paraxial ray approximation (PRA) approach through Akhmanov's nonlinear parabolic wave equation which developed by Sodha [15, 16]. In 1994 Liu and Tripathi used this PRA and WKB approximation to study the competing physical process of self-focusing and diffraction [17]. They found main drawback of the PRA is that it overemphasizes the importance of field close to beam axis and lacks global pulse dynamics. One another global approach is variational approach and it is used in many other branches of science [18-20]. Researcher chooses for the propagation different kind of laser beam profiles like Gaussian beams, cosh-Gaussian beams, Hermite-cosh-Gaussian (HChG) beams, elliptical laser beam, elegant Hermite cosh Gaussian laser beam [21-29] etc.

Self-focusing and cross-focusing of Gaussian electromagnetic beams in fully ionized collisional magnetoplasma investigated by M. S. Sodha. They concluded that self-focusing for high values of the magnetic field and enhance the same for low values of the magnetic field [14]. Dynamics of filament formation in laser produced collisional magneto plasma investigated by A. Singh. they concluded that there is defocusing of spike width for the initial distance of propagation even for different values of initial spike width, as increase the value of 'b' there is decrease in diffraction divergence and self-focusing length is same for different initial values of spike width 'b' and self-focusing length of spike depends on intensity of the main beam and is independent of initial values of the spike width 'b' [30]. M. Jafari investigated evolution of laser beam in warm collisional magneto plasma. Their result shows that external magnetic field causes an increase the strength of self-focusing as well as self-focusing effect can be enhanced by increasing plasma frequency [12]. The variation of spot size of high-power electromagnetic beam in collisional magneto plasma has been analysed by Niknam. They showed that the strength of magnetic field and collision frequency can improve the self-focusing length [31]. The self-focusing of electromagnetic beams in magneto plasma has been analysed by Sodha [32-35].

In present investigation the author has analysed the nonlinear phenomena of self-focusing and defocusing of cosh-Gaussian (ChG) laser beam in collisional magneto plasma [36]. For the simplicity, in common with most investigations the present analysis makes use of the PRA approach given by Akhmanov's and developed by Sodha et al. [15, 16]. Also, author present the propagation of ChG laser beam in collisional magneto plasma; they have studied effect of plasma density on self-focusing. They have also employed two different transverse beam-width parameters in Cartesian coordinate system. The paper is structured as the following: In Section 2, presents brief description of dielectric constant and derived equation for beam width parameters by using WKB and PRA approach in collisional magnetized plasma. In Section 3 detailed discussion of numerical results work carried out for the relevant parameters is given. Last, in section 4 is devoted to conclusions of the present investigation.

Theoretical Consideration

Dielectric Constant of Collisional Magnetized Plasma

We consider the propagation of laser beam in nonlinear medium characterized by dielectric constant of the form [37- 42].

$$\varepsilon_{\pm} = \varepsilon_{0\pm} + \Phi_{\pm}(A\,A^{*}) \tag{1a}$$

$$\varepsilon_{0\pm} = 1 - \frac{\omega_p^2/\omega^2}{1 \mp \frac{\omega_c}{\omega})} \tag{1b}$$

$$\omega_p = \left(\frac{4\pi N_0 e^2}{m}\right)^{1/2} \tag{1c}$$

$$\omega_c = \frac{eB_0}{mc} \tag{1d}$$

$$\Phi_{\pm} = \frac{\omega_p^2}{\omega^2 (1 \mp \frac{\omega_c}{\omega})}\left(\frac{N_0 - N_e}{N_0}\right) \tag{1e}$$

$$\alpha = \frac{8}{3}\alpha_0 \frac{M}{m} \tag{1f}$$

$$\alpha_0 = \frac{e^2}{6\, m\omega^2 k_B T} \tag{1g}$$

$$\frac{N_0 - N_e}{N_0} = \left[1 - \left(\frac{8}{3}\alpha_0 \frac{M}{m}\frac{E^{*}}{\left[1 - \frac{\omega_c}{\omega}\right]^2} * \frac{1}{2 + \frac{8}{3}\alpha_0 \frac{M}{m}\frac{E^{*}}{\left[1 - \frac{\omega_c}{\omega}\right]^2}}\right)\right] \tag{1h}$$

here '$\varepsilon_{0\pm}$' and '$\Phi_{\pm}$' are the linear and nonlinear parts of dielectric constant, respectively, 'ω_p' and 'ω_c' are the plasma frequency and electron cyclotron frequency respectively, *e* and *m* being the magnitude of the electronic charge and rest mass, M is the mass of scattered in the plasma, 'ω' is the frequency of laser used, 'k_B' is the Boltzmann's constant, and 'T' is the plasma temperature scatterer.

Evolution of Beam Width Parameter

We consider the propagation of ChG laser beam through a magneto plasma along the z- direction, which is also the direction of the static magnetic field. The wave equation is considered to comprise two field configurations, the extraordinary mode (right handed circularly polarised) and the ordinary mode (left handed circularly polarised) [35] represented as

$$A_1 = E_X + iE_Y \text{ and } A_2 = E_X - iE_Y \tag{2}$$

where E is the electric vector of the wave which satisfies the wave equation,

$$\nabla^2 E - \nabla(\nabla.E) + \frac{\omega^2}{c^2}(\varepsilon.E) = 0 \tag{3}$$

in component form, Eq. (3) becomes,

$$\frac{\partial^2 E_x}{\partial z^2}+\frac{\partial^2 E_x}{\partial y^2}-\frac{\partial^2}{\partial x}\left(\frac{\partial E_y}{\partial y}+\frac{\partial E_z}{\partial z}\right)=-\frac{\omega^2}{c^2}(\varepsilon.E)_x, \tag{4a}$$

$$\frac{\partial^2 E_y}{\partial z^2}+\frac{\partial^2 E_y}{\partial x^2}-\frac{\partial^2}{\partial y}\left(\frac{\partial E_x}{\partial x}+\frac{\partial E_z}{\partial z}\right)=-\frac{\omega^2}{c^2}(\varepsilon.E)_y, \tag{4b}$$

and

$$\frac{\partial^2 E_z}{\partial x^2}+\frac{\partial^2 E_z}{\partial y^2}-\frac{\partial^2}{\partial z}\left(\frac{\partial E_x}{\partial x}+\frac{\partial E_y}{\partial y}\right)=-\frac{\omega^2}{c^2}(\varepsilon.E)_z, \tag{4c}$$

We assume the variation of field in the z-direction to be more rapid than in the x-y plane so that the wave field can be considered as transverse in the zero-order approximation and hence no space-charge is generated [27]. Then, $\nabla.E=0$ that gives

$$\frac{\partial E_z}{\partial z}=-\frac{1}{\varepsilon_z}\left(\varepsilon_x\frac{\partial E_x}{\partial x}+\varepsilon_y\frac{\partial E_y}{\partial x}+\varepsilon_x\frac{\partial E_x}{\partial y}+\varepsilon_y\frac{\partial E_y}{\partial y}\right) \tag{5}$$

On multiplying Eq. (5) with ± i and adding Eq. (4a) we may obtain

$$\frac{\partial^2 A_1}{\partial z^2}+\frac{1}{2}\left(1+\frac{\varepsilon_{0+}}{\varepsilon_{0z}}\right)\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}\right)A_1+\frac{1}{2}\left(-1+\frac{\varepsilon_{0+}}{\varepsilon_{0z}}\right)\left(\frac{\partial}{\partial x}+i\frac{\partial}{\partial y}\right)^2A_2+\frac{\omega^2}{c^2}$$
$$\times\left[\varepsilon_{0+}+\Phi_+(A_1A_1^*,A_2A_2^*)\right]A_1=0 \tag{6a}$$

$$\frac{\partial^2 A_2}{\partial z^2}+\frac{1}{2}\left(1+\frac{\varepsilon_{0-}}{\varepsilon_{0z}}\right)\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}\right)A_2+\frac{1}{2}\left(-1+\frac{\varepsilon_{0-}}{\varepsilon_{0z}}\right)\left(\frac{\partial}{\partial x}-i\frac{\partial}{\partial y}\right)^2A_1+\frac{\omega^2}{c^2}$$
$$\times\left[\varepsilon_{0-}+\Phi_-(A_1A_1^*,A_2A_2^*)\right]A_2=0 \tag{6b}$$

Although Equations (6a) and (6b) are coupled with each other and the coupling between these two field configurations is not strong [27]. For simplicity we can assume that one of the two field configurations are zero and so we can study the behaviour of self-focusing and self-defocusing of the ChG for another field configuration. On assuming $A_2\approx 0$, Equations (6a) for A_1 gives,

$$\frac{\partial^2 A_1}{\partial z^2}+\frac{1}{2}\left(1+\frac{\varepsilon_{0+}}{\varepsilon_{0z}}\right)\left(\frac{\partial^2}{\partial y^2}\right)A_1+\frac{\omega^2}{c^2}\times\left[\varepsilon_{0+}+\Phi_+(A_1A_1^*)\right]A_1=0 \tag{7}$$

by using Wentzel-Kramer's-Brillouin (WKB) approximation. For the convenience, we can express the solution in the Cartesian coordinate system as

$$A_1=A\ \exp[i(\omega t-k_+z)], \tag{8}$$

where, $k_+=(\omega/c)\varepsilon_{0+}^{1/2}$ and A is a complex amplitude. We substitute equation (8) in (7) and neglect $\partial^2A/\partial z^2$ (Which is equivalent to WKB approximation) we get

$$2ik\frac{\partial A}{\partial z}+\frac{1}{2}\left(1+\frac{\varepsilon_{0+}}{\varepsilon_{0z}}\right)\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}\right)A+\frac{\omega^2}{c^2}\Phi_+(A^*)A=0 \tag{9}$$

by taking $A=A_0(x,y,z)\exp[-ik_+S(x,y,z)]$ Following Akhmanov's et al. (1968) the solution for A_0^2 and S in the Paraxial ray approximation are obtained for extraordinary mode can be written as,

$$A_{0+}^2=\frac{E_0^2}{f_{1+}(z)f_{2+}(z)}\left\{\frac{H_m}{2}\left(\frac{x}{\omega_{0x}}\right)\times\exp\left(\frac{b_x^2}{4}\right)\right.$$
$$\left.\left\{\exp[-\left(\frac{x}{\omega_{0x}}-\frac{b_x}{2}\right)^2]+\exp[-\left(\frac{x}{\omega_{0x}}+\frac{b_x}{2}\right)^2]\right\}\right\}$$
$$\left\{\frac{H_n}{2}\left(\frac{y}{\omega_{0y}}\right)\times\exp\left(\frac{b_y^2}{4}\right)\left\{\exp[-\left(\frac{y}{\omega_{0y}}-\frac{b_y}{2}\right)^2]+\exp[-\left(\frac{y}{\omega_{0y}}+\frac{b_y}{2}\right)^2]\right\}\right\} \tag{10}$$

and

$$S=\beta_{1+}(z)\frac{x^2}{2}+\beta_{2+}(z)\frac{y^2}{2}+\phi(z) \tag{11}$$

where

$$\beta_{1+}(z)=\frac{2}{1+(\varepsilon_{0+}/\varepsilon_{0z})}\frac{1}{f_{1+}}\frac{df_{1+}}{dz}\qquad \beta_{2+}(z)=\frac{2}{1+(\varepsilon_{0+}/\varepsilon_{0z})}\frac{1}{f_{2+}}\frac{df_{2+}}{dz}$$

It is obvious that the parameter $\beta_{1+}(z)$ and $\beta_{2+}(z)$ represents the curvature of the wave front in x and y directions of extraordinary mode. By employing paraxial approximation to obtain the differential equation for the beam-width parameter of ChG laser beam in collisional magnetized plasma for the extraordinary mode. The general beam width parameter differential equations are below,

$$\frac{d^2 f_1}{d\zeta^2}=\left[\left(1+\frac{\varepsilon_{0+}}{\varepsilon_{0z}}\right)^2(1-b_x^2)\right]\frac{1}{f_1^3}-\left[\left(1+\frac{\varepsilon_{0+}}{\varepsilon_{0z}}\right)\right.$$
$$\left.\frac{6(b_x^2-2)\alpha E_0^2\rho^2 M\ \omega^2(1-\omega_c/\omega)\omega_p^2}{\{4\alpha E_0^2M\omega^2f_1+3m\omega(1-\omega_c/\omega)^2f_2^2f_1\}^2}\right] \tag{12}$$

$$\frac{d^2 f_2}{d\zeta^2}=\left[\left(1+\frac{\varepsilon_{0+}}{\varepsilon_{0z}}\right)^2(1-b_y^2)\right]\frac{1}{f_2^3}-\left[\left(1+\frac{\varepsilon_{0+}}{\varepsilon_{0z}}\right)\right.$$
$$\left.\frac{6(b_y^2-2)\alpha E_0^2\rho^2 M\ \omega^2(1-\omega_c/\omega)\omega_p^2}{\{4\alpha E_0^2M\omega^2f_2+3m\omega(1-\omega_c/\omega)^2f_2^2f_1\}^2}\right] \tag{13}$$

where 'R_d' is the diffraction length and 'ζ' is the dimensionless distance of propagation. Similar equation can be obtained for the Ordinary mode by replacing ω_c with - ω_c and changing the subscript from '+' to '–' of f_1 and f_2.

Result and Discussions

Equations (12) and (13) are the second-order, nonlinear, coupled, partial, differential equations which govern self-focusing and defocusing of cosh-Gaussian laser beam in collisional magnetized plasma for *extraordinary* mode. The first term on right hand side of the equations (12) and (13) represents diffraction effect which is responsible for divergence of laser beams (i.e. defocusing effect) as the beam propagates in medium and second term is due to the parabolic nonlinearity in dielectric constant which is responsible for convergence of the laser beams (i.e. focusing effect).

We have displayed the behaviour of f_1 & f_2 with ζ for the cosh-Gaussian laser beams in collisional magnetized plasma in the form of graphs. Final *BWP's* equations have been solved numerically by choosing following numerical parameters for different values of b, Laser beam diameter (1.55μm), laser frequency (ω = 1.78 ×10^{14} *rad*. Sec^{-1}), plasma frequency (ω_p= 5.640× 10^{13}*rad*. Sec^{-1}).

By solving the final Beam width parameter differential equations numerically one can study the non-linear propagation of the cosh-Gaussian laser beam in collisional magnetized plasma for *extraordinary* mode (i.e. E-mode). By using these equations maximum and minimum critical electric field (αE_0^2) were calculated. These final Beam width parameter differential equations gives maximum and minimum critical electric fields along x direction (i.e. αE_{0x1}^2 and αE_{0x2}^2) and along y direction (i.e. αE_{0y1}^2 and αE_{0y2}^2). Out of these four critical electric fields, two fields are lower and two fields are higher.

Following regions (eqn. 14, 15, 16) makes by taking various values of αE_0^2. First region shows choosing value of αE_0^2 is higher as compared to calculated lower and higher αE_0^2. Second region shows choosing value of αE_0^2 is in between of calculated lower and higher αE_0^2 and third region shows choosing value of αE_0^2 is lower than the calculated lower and higher αE_0^2 .

$$\alpha E_{0crx1y1}^2 \rangle \alpha E_{0crx2y2}^2 \rangle \alpha E_{0crxy}^2 \tag{14}$$

$$\alpha E_{0crx1y1}^2 \rangle \alpha E_{0crxy}^2 \rangle \alpha E_{0crx2y2}^2 \tag{15}$$

$$\alpha E_{0crxy}^2 \rangle \alpha E_{0crx1y1}^2 \rangle \alpha E_{0crx2y2}^2 \tag{16}$$

Figure.1 shows that, variation of Beam Width Parameters (f_1&f_2) with dimensionless distance of propagation normalized propagation distance (ζ), by choosing the critical electric fields lies in above the critical region in both x and y direction. Self-focusing and defocusing of laser beam shows in present graph. In the region $\alpha E_{0crx1y1}^2 \le \alpha E_{0crx2y2}^2 \le \alpha E_{0crxy}^2$ the f_1&f_2 both defocuses while in the region $\alpha E_{0crx1y1}^2 \le \alpha E_{0crxy}^2 \le \alpha E_{0crx2y2}^2$ and $\alpha E_{0crxy}^2 \le \alpha E_{0crx1y1}^2 \le \alpha E_{0crx2y2}^2$ the f_1&f_2 has been found to focus. It is observed that, f_1&f_2 travels over a long-normalized propagation distance through collisional magnetized plasma. In both of critical electrical fields region, behaviour of f_1&f_2 are found oscillatory focusing nature. The self-focusing of the f_1&f_2 initially takes place in x & y directions. The f_1&f_2 focuses more and more into plasma the diffraction term and non-linear term compete with each other to cause of beam oscillations.

Figure. 2 shows, the variation of beam width parameters with normalized propagation distance, with different decentred parameter (b). In present case author have chosen decentred parameters in range 0.0 ≤ b ≤ 0.9. From figure it is observed that, behaviour of beam width parameters f_1&f_2 are oscillatory focusing in nature. When increase, decentred parameter values the self-focusing length decreases and beam width parameter f_1&f_2 increases. Stronger self-focusing is observed for higher decentred parameter value as compared to other decentred parameter value. In present result it is also observed that, beam width parameters f_1&f_2 overlaps on each other therefore the behaviour of beam width parameters f_1&f_2 are same.

Figure. 3 shows variation of beam width parameters with normalized propagation distance (ζ), in the present investigation author observed, effect of plasma density on self-focusing for decentred parameter value b=0 (i.e. Gaussian). Author has chosen range of plasma density (0.1 ≤ ω_p/ ω ≤ 0.4). The parameter 'ω_p' is concerned with plasma density. For higher density value the behaviour of both beam width parameters f_1 and f_2 is oscillatory focusing in nature. It is observed that for higher plasma density, strength of the self-focusing is more. It is also observed, when increase in plasma density, self-focusing distance decreases. In case of lower plasma density, the beam width parameters f_1&f_2 gets defocused.

Figure. 4 shows variation of beam width parameters with normalized propagation distance (ζ), in the present investigation author observed, effect of magnetic field on self-focusing for decentred parameter value b=0 (i.e. Gaussian). The parameter 'ω_c' is concerned with magnetic field in plasma. From figure, it is observed that, the increased parameter of 'ω_c' leads to decrease the self-focusing distance of beam. Here we also observed that during propagation for different magnetic field parameters (0.1 ≤ ω_c / ω ≤ 0.4) both the beam width parameters f_1 and f_2 are propagate oscillatory in motion.

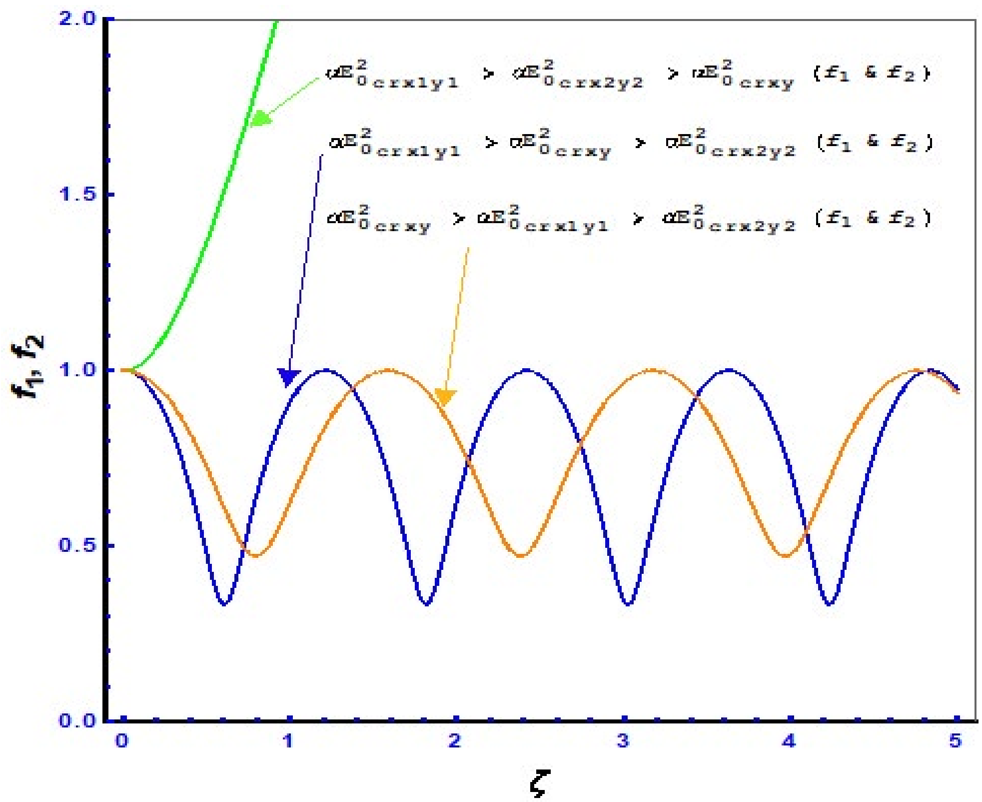

Figure: 1) Variation of the beam width parameters (f_1&f_2) with normalized propagation distance (ξ) for different regions of Critical electric field.

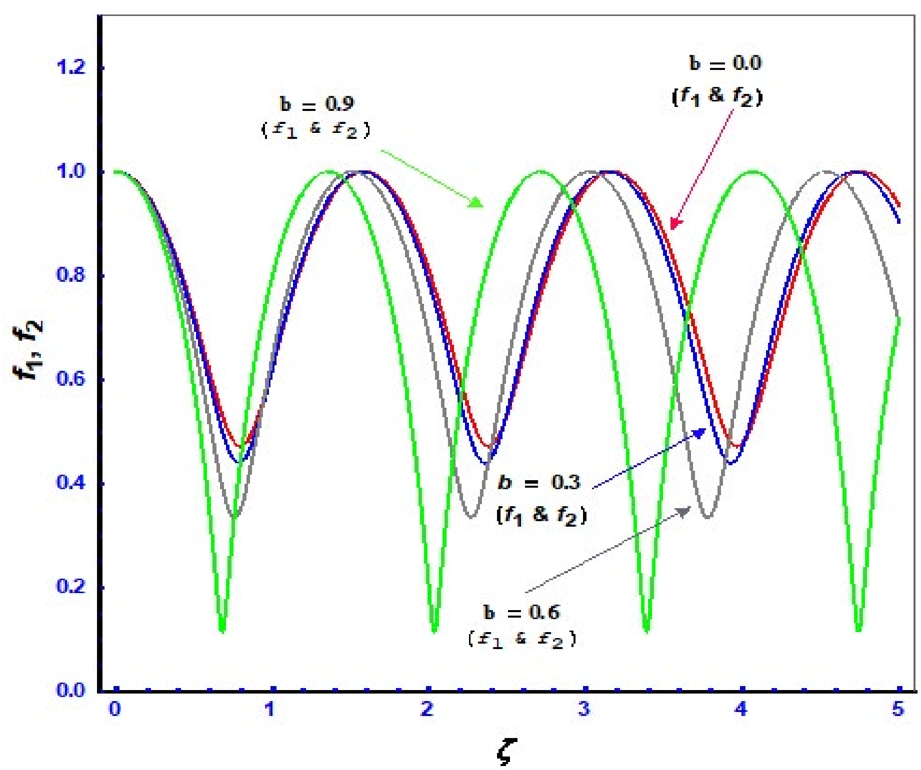

Figure: 2) Variation of the beam width parameters (f_1&f_2) with normalized propagation distance (ξ) for different decentred parameter values.electric field.

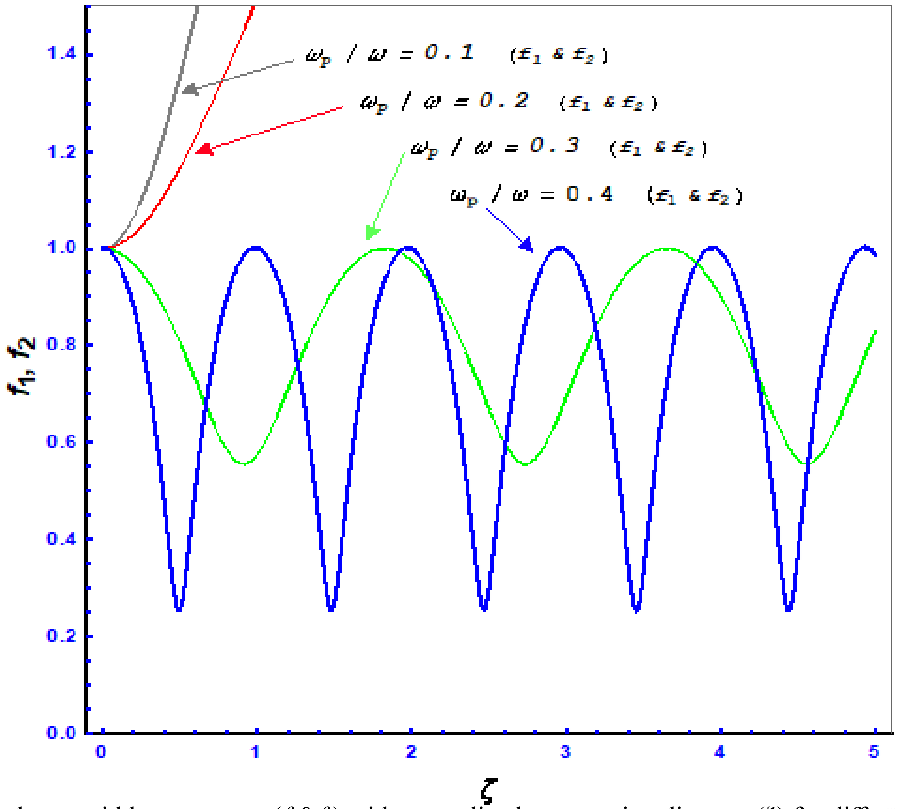

Figure: 3) Variation of the beam width parameters (f_1&f_2) with normalized propagation distance (ξ) for different plasma density values.

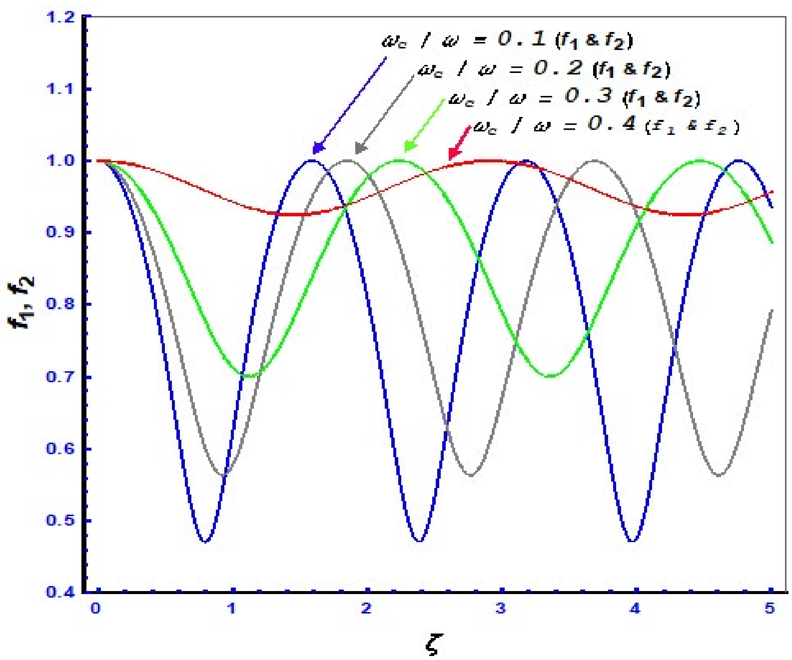

Figure: 4 Variation of beam width parameters (f_1&f_2) with normalized propagation distance (ξ) for different magnetic field values in plasma.

Conclusion

In present theoretical investigation, the second order, non-linear, partial, coupled, differential equation of beam-width parameters have been established by using parabolic wave equation approach under PRA and WKB approximation. Author has investigated non-linear effect of magnetic field, decentred parameter and effect of plasma density on Self-focusing of Cosh-Gaussian laser beams in collisional magnetized plasma.

For a range of lower and higher values of critical electric fields the beams f_1 and f_2 has been found to focusing and defocusing nature. For higher critical electric field beams f_1 and $f2$ has been found nonlinear, oscillatory focusing nature while lower critical electric field beams f_1 and f_2 gets defocused.

In general, for ranges of minimum and maximum values of decentred parameter ($0.0 \leq b \leq 0.9$) the cosh-Gaussian laser beam has been found to focusing nature. The self-focusing length is small for minimum ($0.0 \leq b \leq 0.9$) decentred parameter value. The beam width parameters f_1 and f_2 travel periodically over a long-normalized propagation distance and beams f_1 and f_2 overlaps on each other.

In the effect of plasma density on self-focusing for the extraordinary mode, Author have chosen decentred parameter value b = 0 (i.e. Gaussian). Here, it is observed that, for higher density of plasma leads to the nonlinear self-focusing ($0.1 \leq \omega p/\omega \leq 0.4$) while lower density of plasma, beams f_1 and f_2 gets defocused.

We studied the effect of magnetic field on self-focusing for the extraordinary mode. It is observed that in presence of magnetic field has significant role in enhancement of self-focusing direction of propagation. It is observed that when increase the values of magnetic field parameter the self-focusing length increases and hence self-focusing ability of beam enhances to a greater extent.

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