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STATIC MAGNETIC FIELD INFLUENCE ON PONDEROMOTIVE SELF FOCUSING OF LASER BEAM THROUGH PLASMA

MUNTHER B. HASSAN, ADNAN F. HASSAN & ASRAA SALEM OBEIS
Department of Physics, Faculty of Science, University of Kufa, Najaf, Iraq

ABSTRACT

The nonlinear dielectric constant of magnetized plasma due to its nonlinear interaction with high intense laser beam is derived. Operating the ponderomotive force, the influence of both longitudinal and transverse external magnetic fields on laser beam self-focusing inside collisionless plasma have been calculated. The results show a well enhancement in beam self-focusing when both longitudinal and transverse magnetic fields are increased. Furthermore, in presence of longitudinal magnetic field, the self-focusing of laser beam is greater in comparing with transverse magnetic field.

KEYWORDS: Ponderomotive Nonlinearity, Self-focusing, Longitudinal and Transverse Magnetic Field

1. INTRODUCTION

Recently the investigations of laser plasma nonlinear interactions have great attraction by theoretical and practical researches [1-4]. One of the important phenomena at laser plasma nonlinear interaction is the self-focusing of Gaussian laser beam due to its relevance with very important applications such as x-ray lasers, laser-driven fusion, generation of strong terahertz radiation and laser-driven accelerators [5-10].

In this article, operating the ponderomotive force, one may investigate the nonlinear self-focusing of an intense laser beam through plasma in presence of two external configurations of static magnetic field longitudinally and transversely with respect to laser beam propagation direction. Appropriated expressions will introduce in section 2 to calculate the nonlinear dielectric tensor of magnetized plasma. In section 3, the beamwidth parameter equations of laser beam self-focusing in both longitudinal and perpendicular magnetic fields will derive. In Section 4, the rich discussion of the numerical results and final conclusions will introduce in presence of typical parameters of the laser beam, plasma and magnetic fields.

2. NONLINEAR DIELECTRIC TENSOR

The nonlinearity in the dielectric tensor of the plasma is arising through the ponderomotive force which is exerted on the electrons of plasma and subsequent redistribution it along the wave front. In the ponderomotive nonlinearity, due to nonuniform intensity profile of laser beam, the electrons will travel from the region of low electric field toward the region of high electric field. Thus the electron density is minimum on the laser beam axis and decreases away from it, so the dielectric constant is maximum on the laser beam axis and decreases away from it.

2.1 Nonlinear Dielectric Tensor in Presence of Longitudinal Magnetic Field

Suppose a Gaussian laser beam is propagating in a uniform magnetoplasma of equilibrium electron density n_0

along the direction of a static magnetic field $\vec{B}_0 = \hat{z}B_0$, so the Gaussian laser beam will turn out a circular polarized wave. The electric field vector $\vec{E}_{0+}$ of laser beam propagating along z -direction via the magnetoplasma can be written as [11]

$$\vec{E}_{0+} = \vec{A}_{0+} \exp i\,(\omega_0 t - k_{0+} z\,), \tag{1}$$

Where $\vec{A}_{0+} = \vec{E}_x + i\vec{E}_y$ is the electric field amplitude of a right circular polarized electromagnetic wave, ω_0 and k_{0+} are the angular frequency and wave vector respectively. It is important to mention that the index (+) denotes the right circular polarized mode.

The dispersion relation of a right circular polarized electromagnetic wave propagated through plasma is

$$k_{0+}^2 = \frac{\varepsilon_{0+}\omega_0^2}{c^2},$$

Where c is the light velocity in the vacuum, $\varepsilon_{0+} = 1 - \frac{\omega_p^2}{\omega_0^2}\frac{1}{\left(1 - \frac{\omega_{ce}}{\omega_0}\right)}$ is the dielectric constant, $\omega_p = \left(\frac{4\pi n_0 e^2}{m_e}\right)^{1/2}$ is the plasma frequency, $\omega_{ce} = \frac{eB_0}{m_e c}$ is the electron cyclotron frequency, n_0 is the equilibrium plasma density, e and m_e are the charge and rest mass of electron.

The equation of laser beam intensity, showing Gaussian distribution profile, is given by

$$A_{0+}A_{0+}^* = E_{00}^2 \exp\left(-\frac{r^2}{r_0^2}\right) \tag{2}$$

Where $r^2 = x^2 + y^2$, E_{00} and r_0 are the axial amplitude and initial width of main beam respectively.

Due to the Gaussian distribution of laser beam intensity, a ponderomotive force may be effected as long as τ_p □ r_0 / C_s where r_0 and C_s are the laser beam diameter (measured at FWHM) and ion sound speed respectively, which modifies the plasma density profile n_0 along wavefront of laser beam to be [12].

$$n_e = n_0 \exp\left(-\alpha_+ A_{0+} A_{0+}^*\right) \tag{3}$$

Where T and k_B are the equilibrium temperature of the plasma and the Boltzman's constant and α_+ is the nonlinearity parameter given by

$$\alpha_{+} = \frac{e^{2}\left(1-\frac{\omega_{ce}}{2\omega_{0}}\right)}{16k_{\beta}m_{e}\omega_{0}T\left(1-\frac{\omega_{ce}}{\omega_{0}}\right)^{2}} \tag{4}$$

The equation of electron motion in presence of laser beam and longitudinal external magnetic field is

$$m_{0}\frac{\partial}{\partial t}\vec{\upsilon} = -e\vec{E} - \frac{e}{c}\left(\vec{\upsilon}\times\vec{B}_{0}\right), \tag{5}$$

Where $\vec{\upsilon}$ is the oscillation velocity imparted by laser beam.

Solving Eq. (2), the electron oscillating velocity $\left(\upsilon_{0+}\right)$ at right circular polarized laser beam may be given as

$$\vec{\upsilon}_{0+} = \vec{\upsilon}_{x} + i\,\vec{\upsilon}_{y} = \frac{ie\vec{E}_{0+}}{m_{0}\omega_{0}(1-\frac{\omega_{ce}}{\omega_{0}})}, \tag{6}$$

The current density in term of the electron oscillating velocity $\vec{\upsilon}_{0+}$ and the conductivity tensor $\underline{\underline{\sigma}}$ is given by the following equations [8]

$$J_{0+} = -en_{e}\vec{\upsilon}_{0+} \tag{7}$$

$$J_{0+} = \underline{\underline{\sigma}}E_{0+} \tag{8}$$

Where n_{e} is the local plasma density.

Introducing the effective complex dielectric tensor $\underline{\underline{\varepsilon}}$ in term of conductivity tensor as follows

$$\underline{\underline{\varepsilon}} = \underline{\underline{I}} + \left(\frac{4\pi}{i\,\omega_{0}}\right)\underline{\underline{\sigma}} \tag{9}$$

Now using Eqs. (6-9), the dielectric components may be written as follows

$$\varepsilon_{xx} = \varepsilon_{yy} = 1-\omega_{p}^{2}\Big/\left(\omega_{0}^{2}-\omega_{c}^{2}\right),$$

$$\varepsilon_{xy} = -\varepsilon_{yx} = -i\,\left(\omega_{c}/\omega_{0}\right)\omega_{p}^{2}\Big/\left(\omega_{0}^{2}-\omega_{c}^{2}\right),$$

$$\varepsilon_{xz} = \varepsilon_{zx} = \varepsilon_{yz} = \varepsilon_{zy} = 0,$$

The effective dielectric constant ε_{+} corresponded to the right circularly polarized laser beam will take the following form [12]

$$\varepsilon_{+} = \varepsilon_{xx} - i\,\varepsilon_{xy} = 1 - \frac{\dfrac{\omega_{pe}^{2}}{\omega_{0}^{2}}}{\left(1 - \dfrac{\omega_{ce}}{\omega_{0}}\right)}, \tag{10}$$

Also the effective dielectric tensor ε_{+} can be written as linear ε_{0+} and nonlinear $\varepsilon_{2+}(A_{0+}A_{0+}^{*})$ components as follows [13].

$$\varepsilon_{+} = \varepsilon_{0+} + \varepsilon_{2+}(A_{0+}A_{0+}^{*}) \tag{11}$$

Where $\varepsilon_{2+} = \dfrac{\omega_{p}^{\,2}}{\omega_{0}^{\,2}} \dfrac{\left\{1 - \exp\left(-\alpha_{+}\right) A_{0+}A_{0+}^{*}\right\}}{\left(1 - \dfrac{\omega_{ce}}{\omega_{0}}\right)}$ (12)

The nonlinear part ε_{2} is corresponding to the nonlinear ponderomotive force as a result of nonlinear interaction between Gaussian laser beam and magnetized plasma.

2.2 Nonlinear Dielectric Tensor in Presnce of Transveerse Magnetic Field

To calculate the nonlinear dielectric tensor in presence of transverse magnetic field, one may use same technique as in case of longitudinal magnetic field but taken into account that in this case the propagation of extraordinary laser beam (X-mode) inside homogeneous magnetized plasma is along x-direction and perpendicular on an external magnetic field $\vec{B}_{0}$ which it aligned in z-direction. The variation of the electric field $\vec{E}_{0}$ of the X-mode may be written as follows

$$\vec{E}_{0} = \left(E_{x}\hat{x} + E_{y}\hat{y}\right)\exp - i\left(\omega_{0}t - k_{0}x\right), \tag{13}$$

Therefore the components of the dielectric tensor $\underline{\underline{\varepsilon}}$ will be as following

$$\varepsilon_{xx} = \varepsilon_{yy} = 1 - \frac{\omega_{pe}^{2}}{\omega_{0}^{2}\left(1 - \dfrac{\omega_{ce}^{2}}{\omega_{0}^{2}}\right)},$$

$$\varepsilon_{xy} = -\varepsilon_{yx} = \frac{-i\left(\dfrac{\omega^{2}{}_{pe}}{\omega_{0}^{2}}\right)\left(\dfrac{\omega_{ce}}{\omega_{0}}\right)}{\left(1 - \dfrac{\omega_{ce}^{2}}{\omega_{0}^{2}}\right)},$$

$$\varepsilon_{yz} = \varepsilon_{zy} = \varepsilon_{xz} = \varepsilon_{zx} = 0,$$

$$\varepsilon_{zz} = 1 - \frac{\omega_{pe}^2}{\omega_0^2},$$

By following Ashok K. Sharma (1977) [3], the effective dielectric constant of magnetized plasma in presence of X-mode may be given as

$$\varepsilon = \left(\frac{2\varepsilon_{+}.\varepsilon_{-}}{\varepsilon_{+} + \varepsilon_{-}}\right) = 1 - \left(\frac{\omega_{pe}^2}{\omega_o^2}\frac{\left(\omega_o^2 - \omega_{pe}^2\right)}{\left(\omega_o^2 - \omega_u^2\right)}\right), \tag{14}$$

Where $\varepsilon_{\pm} = \varepsilon_{xx} \mp i\,\varepsilon_{xy}$ and $\omega_u = \left(\omega_{pe}^2 + \omega_{ce}^2\right)^{\frac{1}{2}}$ is the angular frequency of the upper hybrid wave.

As mention early, the Gaussian profile of laser beam intensity will modify the local electronic plasma density n_0 due to ponderomotive force to be

$$n_e = n_0 \exp(-\alpha A_o A_o^*) \tag{15}$$

Where α is the nonlinearity parameter corresponding to the extraordinary mode which is given as

$$\alpha = \frac{e^2}{4m_e\omega_o^2 k_B\left(T_e + T_i\right)} \approx \frac{e^2}{4m_e\omega_o^2 k_B T_o}, \tag{16}$$

Here T_e and T_i are the electron and ion temperatures supposing that $T_i \ll T_e = T_o$.

Rewriting the effective dielectric constant (Eq. 14) using Eq. (15) and Eq. (16), one may obtain

$$\varepsilon = \varepsilon_0 + \varepsilon_2 A_0 A_0^* \tag{17}$$

Where $\varepsilon_o = \left(1 - \frac{\omega_{po}^2}{\omega_o^2}\frac{\left(\omega_o^2 - \omega_{po}^2\right)}{\left(\omega_o^2 - \omega_{po}^2 - \omega_c^2\right)}\right)$ (18)

$$\varepsilon_2 = \alpha\left(1 + \frac{\omega_c^2\left(\omega_o^2 - \omega_c^2\right)}{\left(\omega_o^2 - \omega_{po}^2 - \omega_c^2\right)^2}\right)\left(\frac{\omega_o^2}{\omega_o^2 - \omega_c^2} + \frac{\omega_c^2}{\omega_o^2 - \omega_{po}^2 - \omega_c^2}\right) \tag{19}$$

The first term ε_o represents the linear part of effective dielectric constant in absence of Gaussian laser beam whereas the second term ε_2 is the nonlinear part appearing due to nonlinear ponderomotive force.

3. PONDEROMOTIVE SELF-FOCUSING

Due to the nonlinear dielectric tensor (i.e. nonlinear refractive index), the phase velocity of the laser beam at center will be slower than those at laser beam ends. So the plasma will act as a positive lens leading to induce a self-focusing of laser beam.

3.1 Ponderomotive Self-focusing in Presence of Lngitudinal Magnetic Field

Introducing the wave equation of RCP laser beam propagating through magnetized plasma as follows [9]

$$\nabla^2 \vec{E}_o = \nabla\left(\vec{\nabla}\cdot\vec{E}_o\right) - \frac{\omega_o^2}{c^2}\left(\underline{\underline{\varepsilon_+}}\cdot\vec{E}_o\right), \tag{20}$$

The electromagnetic wave propagating inside magnetized may be considered as a transverse wave since its field varies along longitudinal magnetic field (i.e. z -direction) is larger than its variation via wave front plane (i.e. $x - y$ plane) so that the waves can be treated as transverse in the zeroth order approximation and hence no charge of space is generated in the plasma [3], thus

$$\vec{\nabla}.\underline{\underline{D}} = \vec{\nabla}.\left(\underline{\underline{\varepsilon_+}}.E\right) = 0 \tag{21}$$

Putting components of dielectric tensor in presence of longitudinal magnetic field in above equation (Eq. 21) one may get

$$\frac{\partial E_z}{\partial z} \cong -\frac{1}{\varepsilon_{zz}}\left[\varepsilon_{xx}\left(\frac{\partial E_x}{\partial x} + \frac{\partial E_y}{\partial y}\right) + \varepsilon_{xy}\left(\frac{\partial E_y}{\partial x} - \frac{\partial E_x}{\partial y}\right)\right], \tag{22}$$

Using Eq.(22) and introducing zero-order approximation so Eq.(20) may be written as [14]

$$\frac{\partial^2 A_{o+}}{\partial z^2} + \frac{1}{2}\left(1 + \frac{\varepsilon_{o+}}{\varepsilon_{ozz}}\right)\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\right)A_{o+} + \frac{\omega_o^2}{c^2}\left(\varepsilon_{o+} + \varepsilon_{2+}A_{o+}A_{o+}^*\right)A_{o+} = 0, \tag{23}$$

These equations have been written in the first order approximation; i.e. the product of nonlinear part with $\frac{\partial^2 A_{o+}}{\partial x^2}$ or $\frac{\partial^2 A_{o+}}{\partial y^2}$ have been neglected.

Introducing $A_{o+} = A'_{o+} \exp i\left(\omega_o t - k_{o+} z\right)$, where A'_{o+} is a complex amplitude, one may rewrite Eq. (23) to be

$$-2ik_{o+}\frac{\partial A'_{o+}}{\partial z} + \frac{1}{2}\left(1 + \frac{\varepsilon_{o+}}{\varepsilon_{ozz}}\right)\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\right)A'_{o+} + \frac{\omega_o^2}{c^2}(\varepsilon_{2+}A'_{o+}A'^*_{o+})A'_{o+} = 0, \tag{24}$$

Last equation may be separated to real and imaginary parts by supposing $A'_{o+} = A^o_{o+}\exp\left(ik_{o+}S_+\right)$, where A^o_{o+} and S_+ are a real function and the phase of the RCP laser beam inside magnetoplasma respectively, and Proposing $\frac{\partial}{\partial y} = 0$ for a two dimensional Gaussian laser beam so [3]

$$2\frac{\partial S_+}{\partial z}+\frac{1}{2}\left(1+\frac{\varepsilon_{o+}}{\varepsilon_{ozz}}\right)\left(\frac{\partial S_+}{\partial x}\right)^2-\frac{1}{2k_{o+}^2A_{o+}^o}\left(1+\frac{\varepsilon_{o+}}{\varepsilon_{ozz}}\right)\frac{\partial^2A_{o+}^o}{\partial x^2}=\frac{\varepsilon_{2+}}{\varepsilon_{o+}}\left(A_{o+}^o\right)^2, \tag{25}$$

$$\frac{\partial\left(A_{o+}^o\right)^2}{\partial z}+\frac{1}{2}\left(A_{o+}^o\right)^2\left(1+\frac{\varepsilon_{o+}}{\varepsilon_{ozz}}\right)\frac{\partial^2S_+}{\partial x^2}+\frac{1}{2}\left(1+\frac{\varepsilon_{o+}}{\varepsilon_{ozz}}\right)\frac{\partial S_+}{\partial x}\frac{\partial\left(A_{o+}^o\right)^2}{\partial x}=0. \tag{26}$$

Using the paraxial ray theory for simplicity, the phase function S_+ may be expanded to become

$$S_+=\frac{1}{2}x^2\beta_+(z)+\varphi_+(z)$$

Where β_+^{-1} may refer to the curvature radius of laser beam and φ_+ is a constant independent of $x-$direction.

To more understanding of nonlinear behavior of laser beam inside magnetized plasma, one may introduce the beam width parameter f_+ concept within initially Gaussian laser beam as follows

$$\left(A_{o+}^o\right)^2=\frac{E_{oo}^2}{f_+}\exp\left(-\frac{x^2}{x_o^2f_+^2}\right)$$

Where x_o is the initial beam radius before its propagation through plasma.

Also substituting S_+ in Eq. (26), $\beta_+(z)$ will take the following form [13]

$$\beta_+(z)=2\left(1+\frac{\varepsilon_{o+}}{\varepsilon_{ozz}}\right)^{-1}\frac{1}{f_+}\frac{df_+}{dz},k$$

Rewrite Eq. (26), Using A_{o+}^o and $\beta_+(z)$ values, assuming initially plane wavefront boundary conditions (at $z=0:f_+=1$ and $\frac{df_+}{dz}=0$), one may obtain

$$\frac{d^2f_{o+}}{dz^2}=\frac{\left(1+\frac{\varepsilon_{o+}}{\varepsilon_{zz}}\right)^2}{4R_{d+}^2f_{o+}^3}-\frac{(1-\varepsilon_{o+})}{2\varepsilon_{o+}}\frac{\left(\frac{\alpha_+E_{oo}^2}{f_{o+}}\right)\left(1+\frac{\varepsilon_{o+}}{\varepsilon_{zz}}\right)}{x_o^2f_{o+}^2} \tag{27}$$

$R_{d+}=k_{o+}x_o^2$ is the diffraction length related with RCP laser beam. The last equation may rewrite by introducing the normalized propagation distance $\zeta_+=z/R_{d+}$, as follows

$$\frac{d^2 f_{o+}}{d\zeta_+^2} = \frac{\left(1+\frac{\varepsilon_{o+}}{\varepsilon_{zz}}\right)^2}{4f_{o+}^3} - \frac{R_{d+}^2 (1-\varepsilon_{o+})}{2\varepsilon_{o+}} \frac{\left(\frac{\alpha_+ E_{oo}^2}{f_{o+}}\right)\left(1+\frac{\varepsilon_{o+}}{\varepsilon_{zz}}\right)}{x_o^2 f_{o+}^2} \tag{28}$$

The first term on the right-hand side of Eq. (28) is related to the diffraction effect and the second term is related to the focusing effect due to ponderomotive force.

3.2 Laser Beam Self-focusing Mechanism in Transverse Magnetic Feield

To study the nonlinear self-focusing of extraordinary laser beam in presence of transverse magnetic field, taking in our account the variation of nonlinear dielectric tensor in presence of transverse magnetic field so the final equation of beam width parameter f varying extraordinary laser mode via magnetized plasma may be given as

$$\frac{d^2 f}{dz^2} = \frac{1}{R_d^2 f^3} - \frac{\varepsilon_2 E_{oo}^2}{\varepsilon_o x_o^2 f^2} \tag{29}$$

Where $R_d = k_o x_o^2$ represents the diffraction length corresponding to extraordinary laser beam.

Introducing the normalized propagation distance $\zeta = z/R_d$, the last equation may be written as

$$\frac{d^2 f}{d\zeta^2} = \frac{1}{f^3} - \frac{\varepsilon_2 R_d^2 E_{oo}^2}{\varepsilon_o x_o^2 f^2} \tag{30}$$

The last equation represents the ponderomotive nonlinear self-focusing of X-mode laser beam inside plasma in presence of transverse magnetic field. As a result of competition between the diffraction and self-focusing terms (first and second terms on the right hand side of Eq.(30) respectively), the beamwidth parameter f will vary along normalized propagation distance ζ periodically.

FIGURES CAPTION

Figure 1: Variation of beam width parameter f_+ along the normalized propagation distance ζ_+ in presence of high values of longitudinal magnetic field.

Figure 2: Variation of beam width parameter f along the normalized propagation distance ζ in presence of high values of transverse magnetic field.

Figure **Error! No text of specified style in document.**: Variation of beam width parameter along the normalized propagation distance in presence of longitudinal magnetic field (blue dashed line) in once and transverse magnetic field (red solid line) in other.

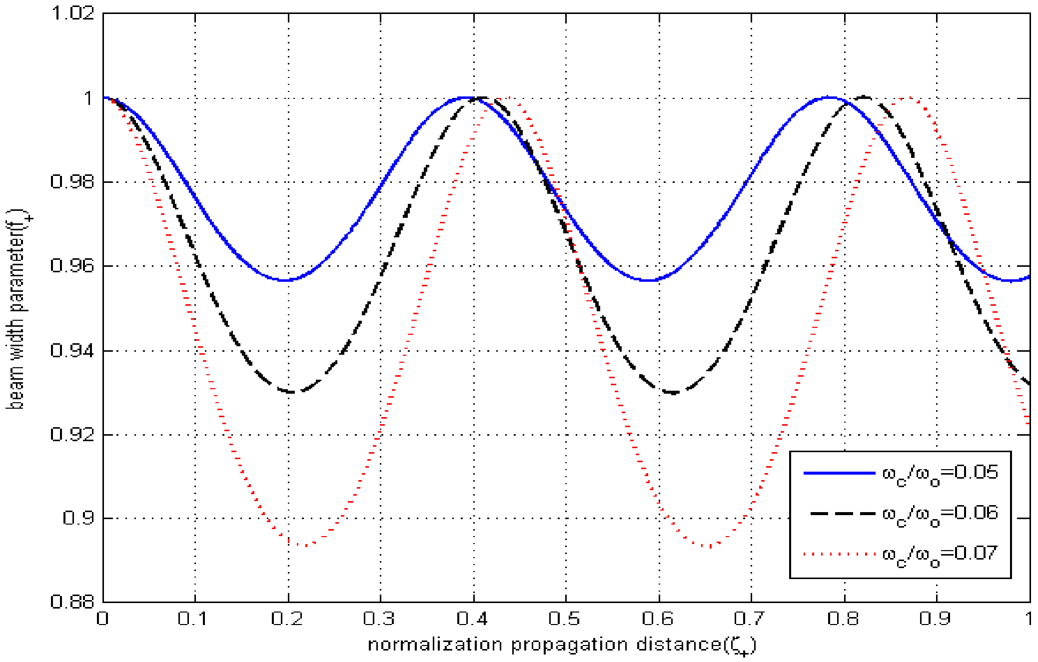

Figure 1: Variation of Beam Width Parameter f_+ Along the Normalized Propagation Distance ζ_+ in Presence of High Values of Longitudinal Magnetic Field

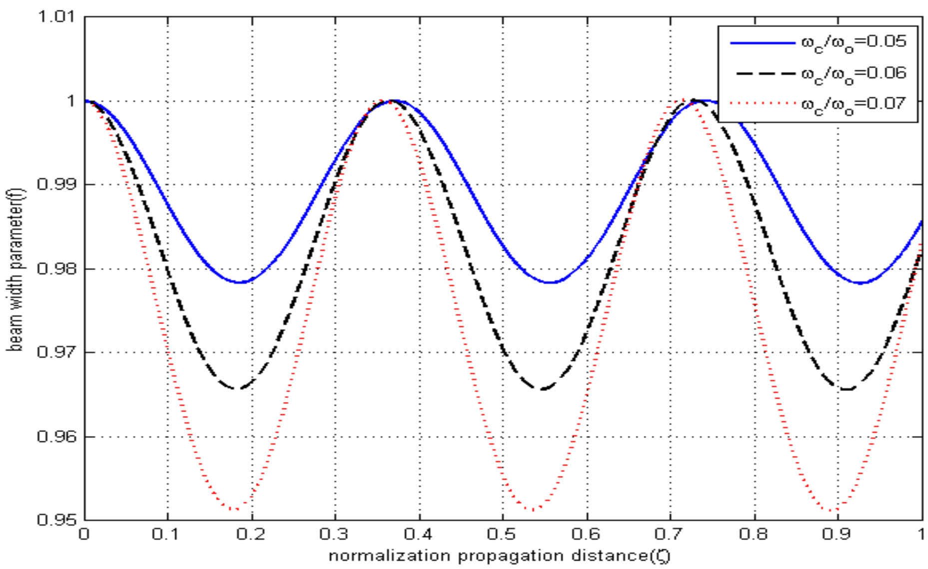

Figure 2: Variation of Beam Width Parameter f Along the Normalized Propagation Distance ζ in Presence of High Values of Transverse Magnetic Field

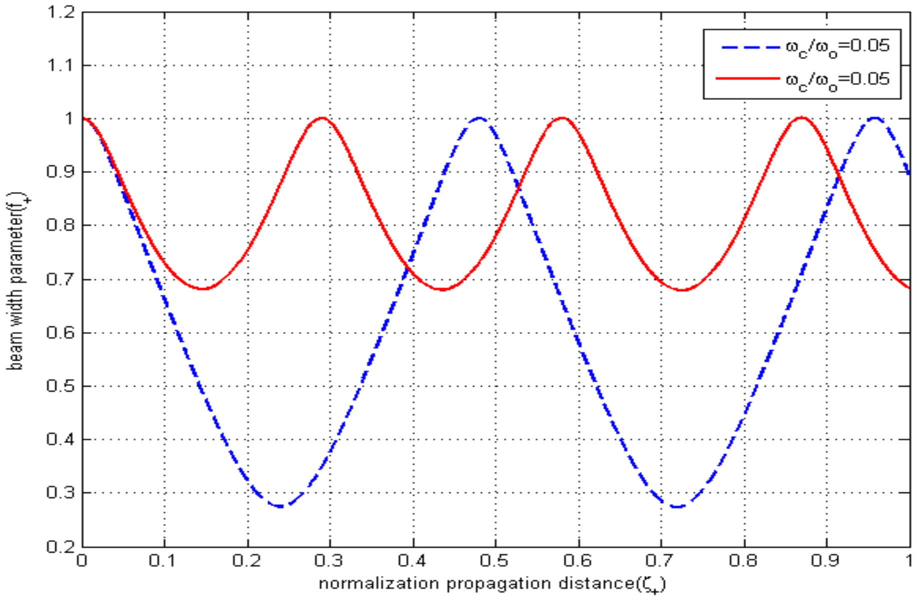

Figure Error! No text of specified style in document.**: Variation of Beam Width Parameter Along the Normalized Propagation Distance in Presence of Longitudinal Magnetic Field (Blue Dashed Line) in Once and Transverse Magnetic Field (Red Solid Line) in Other**

4. RESULT DISCUSSIONS AND CONCLUSIONS

In this article, the typical parameters of laser and plasma are introduced as following:

The laser beam intensities $\left(I = 1\times10^{12}\, W/cm^{2}\right)$, the wavelength of pump laser $(\lambda = 10.6\,\mu m)$ corresponding to angular frequency $\left(\omega_0 = 1.78\times10^{14}\, rad.\sec^{-1}\right)$, the laser beam diameter $\left(x_0 = (50, 60, 70)\,\mu m\right)$, the plasma densities $n_0 = (4.8,\ 6.3,\ 8)\times10^{18} cm^{-3}$ which are corresponded to plasma frequencies $\omega_{pe} = (0.7, 0.8, 0.9)\,\omega_0$.

The presence of magnetic field has significant influence on enhancement the self-focusing of laser beams to be faster and stronger. The external magnetic field geometries (longitudinal or transverse magnetic field) have crucial role on the nonlinear self-focusing of Gaussian laser beam. To understand the nonlinear behavior of laser beam inside magnetized plasma, the equations of laser beam self-focusing for both longitudinal and transverse magnetic fields (i.e. Eq.(28) and Eq.(30) respectively) have been solved numerically.

When the longitudinal magnetic field is raised to high magnitudes range to become $\left(B = 538kG, 645kG \text{ and } 753\text{kG}\right)$ which are corresponding to the $\left(\omega_c = 0.05\omega_o, 0.06\omega_o \text{and } 0.07\omega_o\right)$ respectively, directly the RCP laser beam will undergo a nonlinear self-focusing (see figure 1). Whenever the laser beam diameter reaches to the minimum value, the natural diffraction effect will overcome the nonolinear self-focusing and the RCP laser beam will diverge and so on.

In presence of transverse magnetic field, figure (2) demonstrates the same behavior of Gaussian laser beam when it is propagating through plasma as in case of the longitudinal magnetic field (figure 1) but the states of divergence and convergence will happen slowly which it means that the longitudinal magnetic field has greater effect on propagation of Gaussian laser beam through plasma than transverse magnetic field.

One may conclude that the presence longitudinal external magnetic field is more effect on ponderomotive self-focusing comparing with the transverse external magnetic field (see figuer3).

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