Abstract: The study is a theoretical and simulator study of nonlinear ponderomotive force interaction between RCP laser beam TEM00 and collisionless longitudinal magneto plasma in paraxial region and nonparaxial region. The study includes two important phenomena resulted from the above interaction, which are self-focusing of laser beam and THz radiation generation. Also discussed the behavior of these phenomena at different values of initial laser beam radii and initial plasma density. The aim of study reaches to the physical and mathematical diversion for the equation of self-focusing in paraxial and nonparaxial regions. and diverting the equation of THz radiation propagation through the magneto plasma. The self-focusing in both regions (paraxial and nonparaxial) becomes faster and stronger when the initial laser beam radius is increased. The self-focusing in both regions (paraxial and nonparaxial) becomes faster and stronger when the initial plasma frequency is increased stability is proportional with initial laser beam in both, paraxial and nonparaxial regions without apparent high increase in its amplitude. The stability of THz is higher in nonparaxial than in paraxial region. THz stability is reversely proportional with initial plasma frequency. In this study, Nd:YAB with wavelength of \( \lambda = 1.06 \, \mu m \), intensity of \( 10^{14} \, W/cm^2 \) and pulsed laser is exerted on hydrogen plasma to interact nonlinearity. The following set of parameters has been used in the numerical calculations: Laser intensity \( 10^{14} \, W/cm^2 \). Initial beam radius \( r_0 = (2.4, 2.6, 2.8) \) \( \mu m \). Laser wavelength \( \lambda = 1.06 \, \mu m \). Laser frequency. \( \omega_0 = 1.778 \times 10^{-15} \, \text{rad/s} \). Initial plasma frequency. \( \omega_1 = (0.8, 0.84, 0.88w_0) \, \text{rad/s} \). Applied magnetic field \( B_0 = 60 \, KG \).

Key words: Laser Beam; Magnetized Plasma; Rippled Plasma; Terahertz Generation; ponderomotive force; Nonparaxial region; Paraxial region; self-focusing.

Introduction

Laser and plasma interaction is one of the important phenomena that had the world wide interest of most researchers subject, when a high power electromagnetic wave enters a plasma, a number of nonlinear phenomena can happen; so this interaction is considered a source for many important phenomena are used in technology, such as filamentation or self-focusing, generation of terahertz radiation (THz R), (which will be the research focus of this study). [2,3], stimulated Raman scattering (SRS) [4], stimulated Brillouin scattering (SBS) [5], second harmonic generation (SHG) [10,11], plasma-based acceleration (PBA), laser driven fusion (LDF), and x-ray lasers (XRL) [6,7]. THz radiation depends on self-focusing because we need high intensity laser to generate THz, which will be provided by self-focusing That’s why, we will study both phenomena together. The development of high-power laser led to discover and develop the nonlinear interaction, and the first step of

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this development was achieved by G. Mourou and his co-workers in 1980s, when they successfully used chirp pulse amplification (CPA) technique that produces picoseconds, terawatt laser pulses [8,9]. For instance, table-top lasers, when it’s focused to a 10 μm spot size, can produce high intensity of the order $10^{21}$ W/cm$^2$ at 1.06 μm wavelength [10]. Recently, the production of monochromatic electromagnetic radiation with high intensity, covering all the necessary spectrum, is considered as one of the most significant challenges. THz radiation is one of them. One Terahertz One million-million times per second. "Tera- comes" from a Greek term means ‘marvel’ or ‘monster,’ with the sense that this is a huge and marvelous quantity. At the present time, (THz) physics has become the world wide researchers’ special interest, that’s in turn has been widely used in several applications like security identification [12,13], medical imaging [14,15], and the domain spectroscopy [9-11]. THz radiation intensity is proportional with laser intensity according to laser and plasma interaction that provides us with self-focusing. Then, the intensity of laser rises up to hundred times; so that, laser plasma interaction is considered an important source for generating THz radiation with high intensity and high conversion efficiency. The first direct observation of THz frequency by laser beam has been reported by Hamster et al. [19]. Laser pulses with a power of $10^{12}$ W were focused on both gas and solids targets. First successful operation to produced THz radiation, observed from plasma target, was driven by pondermotive force. Laser and plasma interaction are considered as source of a high intensity laser beam wave that has compatible phase with the electron phase in first Bohr orbit of hydrogen atom. In other words, the rippled plasma wave. The condition of THz generation is the difference between the frequency of laser and plasma in term of THz and the phase between them equals to zero [21]. As a result of the nonlinear interaction, an excitation of electrons happens that leads to two regions in the nonlinear regime in collisionless plasma high and low electrons intensity. The main rule that describe the interaction; depended on laser intensity in term of $10^{12}$ - $10^{14}$ the pondermotive phenomenon considers, $10^{14} \leq$ relativistic mass considers. In this study, we will take the pondermotive force influence to generate THz radiation which represents a result of laser and plasma interaction in presenting longitudinal magnetic field.

Nonlinear Dielectric Constants in present of Longitudinal Magnetic Field:

Consider the propagation of a circularly polarized laser beam of angular frequency $\omega$ in a homogeneous magneto plasma with electronic density $n_e$, along the direction of static magnetic field $B_0$. Figure (1).

The electric field $\vec{E}_{0+}$ wave equation of the right circular polarized laser beam (RCP) propagating along $z$ - direction through the magneto plasma can be written as follows [2]:

$\vec{E}_{0+} = \vec{A}_{0+}(x,y,z) \exp i(\omega t - k_{0z} z)$  \hspace{1cm} (1)

where $\vec{A}_{0+} = \vec{E}_{x} + i\vec{E}_{y}$ represents the electric field amplitude of (RCP) laser beam, $\omega_0$ and $k_{0z}$ are the angular n frequency and the wave vector respectively, $\varepsilon_{0+}$ represents the dielectric constant in linear regime it is related with $k_{0z}^2 = \frac{\varepsilon_{0+} \omega_{0}^2}{c^2}$. $c$ is the light velocity in the vacuum. The electron general motion equation in electromagnetic field is:

$m_e \frac{d^2\vec{u}}{dt^2} = -e\vec{E}_{0+} - \frac{e}{c}(\vec{u} \times \vec{B}_0)$ \hspace{1cm} (2)

Where $\vec{u}$ the oscillating velocity transmit by laser beam. $e$ and $m_e$ represent the charge and mass of electron respectively.
Where $\omega_{op} = \frac{4\pi n_0 e^2}{m_0}$ is the plasma frequency.

We will use the laser beam fundamental mode (TEM00) which is Gaussian profile intensity distribution.

laser beam (TEM00) intensity will redistribute electronic plasma density $n_e$ to become $n_{e+}$ which will stimulate the ponderomotive force [3]:

$$n_{e+} = n_e \exp(-\alpha e A_{0+}^* A_{0+})$$  \hspace{1cm} (3)

Where $\alpha$ is the ponderomotive force nonlinearity parameter represented by the equation [4].

$$\alpha = \frac{e^2}{16 \epsilon_0 m_o c^2 T_e(1-\frac{\omega_p^2}{\omega_0^2})}$$  \hspace{1cm} (4)

Where $k_B$ and $T_e$ are the Boltzmann constant and equilibrium temperature of the plasma.

Electronic plasma density will be redistributed frequently leading to adjust the dielectric constant to become effective dielectric constant which is represented by the following equation [5]:

$$\varepsilon_{+} = \varepsilon_{x x} - i \varepsilon_{x y} = \varepsilon_{+} + \varepsilon_{z+}(A_{0+}^* A_{0+}^*)$$  \hspace{1cm} (5)

The equation above represents the general formula of the dielectric constant of the magnetoplasma in presence longitudinal magnetic field, $\varepsilon_{+}$ represents the liner part which will take the following formula [6]

$$\varepsilon_{0+} = 1 - \frac{\omega_{pe}^2}{\omega_0^2}$$  \hspace{1cm} (6)

$\varepsilon_{z+}(A_{0+}^* A_{0+}^*)$ represents the nonlinear part, due to high intensity laser beam which is represented by the following equation [6]: -

$$\varepsilon_{z+}(A_{0+}^* A_{0+}^*) = \frac{\omega_{pe}^2}{\omega_0^2} \left(1 - \exp(-\alpha e A_{0+}^* A_{0+}^*) \right)$$  \hspace{1cm} (7)

At low laser intensity the nonlinear part, of the effective dielectric constant $\varepsilon_{z+}$ will approach to zero, because of $\alpha A_{0+} A_{0+}^*$ (the ponderomotive force) will approach to zero, the Influence of dielectric constant $\varepsilon_{+}$ will approach to linear dielectric constant $\varepsilon_{0+}$ [7].

Ponderomotive force and Self-Focusing of (RCP) Laser Beam in Nonparaxial region:

When high intensity laser TEM00 crosses plasma, the beam will propagate and interact with plasma into two regions according to mode of wavefront. These two regions are called Nonparaxial and paraxial. The paraxial region is a special case of the Nonparaxial, so the Nonparaxial region will be the general case for laser plasma interaction. As we said that the dielectric constant $\varepsilon_{+}$ will be modified to the effective dielectric constant $\varepsilon_{+eff}$ as a result of electronic plasma density modified in this part. We will derive the general wave equation of RCP laser beam propagates through magnetized plasma by using $\varepsilon_{+eff}$ to understand the nonlinear behavior of laser beam in Nonparaxial region. [8].

$$\varepsilon_{+eff} = \varepsilon_{0+} + \varepsilon_{z+} A_{0+}^* A_{0+}^* = 1 - \frac{\omega_{pe}^2}{\omega_0^2} + \frac{(\omega_{pe}^2 -1) e^{\alpha e A_{0+}^* A_{0+}^*}}{1-\frac{\omega_{pe}^2}{\omega_0^2}}$$  \hspace{1cm} (8)

The propagation of RCP laser beam inside magnetized plasma is governed by the general wave equation as the following:

$$\nabla^2 E_{0+} - \nabla \left( \nabla \cdot E_{0+} \right) + \frac{\omega_p^2}{c^2} E_{0+} = 0$$  \hspace{1cm} (9)

where $E_{0+} = A_{0+}(x,y,z) \exp(i (\omega_0 t - k_{0+} z)$. The electric field of the right circular polarized laser beam (RCP) propagating along $z$ – direction through the magneto plasma [8].

And $A_{0+} = \vec{E}_0 + i \vec{E}_g$ represents the electric field amplitude of (RCP) laser beam, $\omega_0$ and $k_{0+}$ are the angular n frequency and the wave vector respectively, $\varepsilon_{+}$ represents the dielectric constant in linear regime it is related with $k_0^2 = \frac{\omega_0^2}{c^2}$. $c$ is the light velocity in the vacuum. Following Sodha et al. (1974b) method and using Eq. (8) the general wave equation (9) can be written as [63].

$$\frac{\partial^2 A_{0+}}{\partial x^2} + \frac{1}{2} \left(1 + \varepsilon_{zzz} \right) \left( \frac{\partial^2 A_{0+}}{\partial y^2} + \frac{\partial^2 A_{0+}}{\partial z^2} \right) + \frac{\omega_0^2}{c^2} (\varepsilon_{+} + \varepsilon_{z+} A_{0+}^* A_{0+}^*) A_{0+} = 0$$  \hspace{1cm} (10)

The sound dravite four RCP laser beam amplitude (TEM00), $\frac{\partial^2 A_{0+}}{\partial x^2} \frac{\partial^2 A_{0+}}{\partial y^2} \frac{\partial^2 A_{0+}}{\partial z^2}$ have been neglected.

Presenting $A_{0+} = A_{0+}^* \exp (i(\omega_0 t - k_{0+} z)$, where $A_{0+}^* = A_{0+} \exp (ik_{0+} S_x)$ is a complex amplitude, $A_{0+}^*$ and $S_x$ are a real function and the phase function of the laser beam through magnetized plasma respectively, therefore Eq.(10) can be written as [64].

$$2 \frac{\partial^2 A_{0+}}{\partial x^2} + \frac{1}{2} \left(1 + \varepsilon_{zzz} \right) \left( \frac{\partial^2 A_{0+}}{\partial y^2} + \frac{1}{2k_{0+}^2} A_{0+}^* \right)^2 - \frac{\omega_0^2}{2k_{0+}^2} A_{0+}^*$$  \hspace{1cm} (11)

$$\frac{\partial^2 (A_{0+}^*)^2}{\partial z^2} + \frac{1}{2} \left(A_{0+}^* \right)^2 \left(1 + \varepsilon_{zzz} \right) \frac{\partial^2 (A_{0+}^*)^2}{\partial x^2} + \frac{1}{2} \left(1 + \varepsilon_{zzz} \right) \frac{\partial^2 (A_{0+}^*)^2}{\partial y^2} = 0$$  \hspace{1cm} (12)

The two above equations have been separated to real and imaginary parts. In Nonparaxial theory, the real function $A_{0+}^*$ and the phase function $S_x$ depend on the curvature of wavefront of the laser beam.

They are respectively represented as the follows [65].

$$A_{0+}^2 = \frac{E_{0+}^2}{E_{0+}^2 + \frac{\omega_0^2}{r^2} + \frac{\omega_{pe}^2}{r^2} e^{2\frac{\omega_{pe}^2}{c^2}}}$$  \hspace{1cm} (13)

$$S_x = \frac{S_{00} + \frac{\omega_{pe}^2}{r^2}}{S_{00} + \frac{\omega_0^2}{r^2}}$$  \hspace{1cm} (14)

where $f_{0+}$ is the beam width parameter so the dravite $\frac{\partial (A_{0+})}{\partial x}$ represents the variation spot size in other
word focusing and defocusing laser beam during its propagation inside plasma. \( \alpha_{oo} \) represents spherical deformation coefficient of second order. \( \alpha_{oo} \) represents spherical deformation coefficient of fourth order. \( \alpha_{oo}, \alpha_{oz} \) distinguish the Nonparaxial region contribution of the beam intensity. \( S_{oo} \) represents the spherical curvature of the wavefront. \( S_{oz} \) represents the deformation of wavefront from spherical shape.

Substitution equations (15) in (14) and use (14) & (13) in (11) & (12) and equating the coefficients of \( r_0^2 \) and \( r_0 \) of the resulting equation, so the equations of beam width parameter \( f_oo \), and wavefront deformation from the spherical shape \( S_{oz} \) will be as follows:

\[
\begin{align*}
\frac{d^2f_{oo}}{dz^2} &= \frac{1}{4} \left( 1 + \frac{\alpha_{oo} + \alpha_{oz}}{\alpha_{oo}} \right) \left( - \frac{\alpha_{oo} - \alpha_{oz}}{\alpha_{oz}} \right) - \\
& \frac{1}{2} \left( 1 + \frac{\alpha_{oo} + \alpha_{oz}}{\alpha_{oo}} \right) \left( - \frac{\alpha_{oo} - \alpha_{oz}}{\alpha_{oz}} \right) - \\
& \frac{1}{2} \left( 1 + \frac{\alpha_{oo} - \alpha_{oz}}{\alpha_{oz}} \right) \left( - \frac{\alpha_{oo} + \alpha_{oz}}{\alpha_{oz}} \right)
\end{align*}
\]

Equations (17) & (18) are ruling and the density ripple plasma \( r_0 = R_0 \) which represents the defraction length, To be more convenient for numerical programming. The electron density perturbation \( \bar{n}_p \) and the density ripple plasma \( r_0 \) are related by the following equation:

\[
\mu = \frac{n_p}{\mu_0} \frac{v_1}{v_1 - k_0 z}
\]

where \( v_1 = - \frac{ie\hbar}{m_e \omega_1} \) and \( \mu \) are the normalized ripple density amplitude.

The general wave equation for electric field vector \( \vec{E}_{r+} \) propagate through magneto plasma written as (Shukla & Sharma, 1982):

\[
\nabla \times \vec{E}_{r+} = \frac{\sigma_0}{c} \frac{\partial \vec{E}_{r+}}{\partial t} + \frac{1}{c^2} \frac{\partial^2 \vec{E}_{r+}}{\partial t^2}
\]

Nonlinear interaction of a finite-amplitude plasma wave with high-and low frequency circularly polarized waves is governed by continuity equation.

\[
\nabla \cdot (\vec{n}_e \vec{v}_e) + \frac{\partial \vec{n}_e}{\partial t} = 0
\]

(24)

Momentum transfer equation, or motion equation of electron in magneto plasma is represented below:

\[
m_e \frac{\partial \vec{v}_e}{\partial t} = -e \vec{E}_{r+} - \vec{v}_e \times \vec{B}_0 \times \vec{B}
\]

(25)

where \( n_e, m_e, v_e \) are the electron density, mass and velocity respectively \( \vec{B}, \vec{B}_0 \) are the magnetic field ambient of the plasma, the magnetic field of laser wave respectively. \( \vec{B} \) is neglected in our work.

\[
\vec{f}_{r+} = \vec{j}_{r+} + \vec{j}_{r+}^2
\]

(26)

where \( \vec{f}_{r+} \) is the total current density vector in the presence of low frequency electric field \( \vec{E}_{r+} \).
where $\tilde{f}_{1+}$ and $\tilde{f}_{2+}$ are the linear and nonlinear current densities, respectively.

$$\tilde{f}_{1+} = -e\eta_{0}\tilde{v}_{1+} + e\eta_{0}\tilde{v}_{2+}$$

(27)

$$\tilde{f}_{2+} = -e\eta_{0}\tilde{v}_{1+} + e\eta_{0}\tilde{v}_{2+}$$

(28)

In the above equation, $\eta$ and $\eta_{0}$ are charge and density perturbation of the electron, and $\eta_{0}$ is the background density, where $\tilde{v}_{1+}, \tilde{v}_{2+}$ represents the electron and ion linear velocities, which can be extracted by solving momentum equation (2.55):

$$\tilde{v}_{1+} = \frac{i\epsilon\tilde{E}_{r+}}{m_{e}(\omega_{r}-\omega_{ce})}$$

(29)

The linear velocity for ion:

$$\tilde{v}_{1+} = \frac{i\epsilon\tilde{E}_{r+}}{m_{i}(\omega_{r}-\omega_{ce})}$$

(30)

where $\omega_{ce}$ is $eB_{0}/m_{e}c$ is the ion cyclotron frequency with the ion mass $m_{i}$.

Substituting $\tilde{v}_{1+}$ and $\tilde{v}_{2+}$ from Eqs. (29) and (30) into Eq. (27) we find the linear current density $\tilde{f}_{1+}$ for the right circularly mode, so $\tilde{f}_{1+}$ will be:

$$\tilde{f}_{1+} = -im_{e}e^{2}(\frac{\tilde{v}_{2+}}{m_{e}(\omega_{r}-\omega_{ce})\omega_{r}})\tilde{E}_{r+}$$

(31)

The nonlinear velocity $\tilde{v}_{2+}$ is produced by the beating of electron velocity $\tilde{v}_{e+}$ in density ripple with the laser velocity $\tilde{v}_{0+}$, and corresponding to the laser-frequency magnetic field $B_{0} = (c\tilde{E}_{r+}/\omega_{0}) \times \tilde{E}_{r+}$, $\tilde{v}_{2+}$ is obtained by solving the following equation (Shukla & Sharma, 1982):

$$\frac{d}{dr}\tilde{v}_{2+} + \omega_{r}\tilde{v}_{2+} \times \hat{z} = -m_{e}v^{*}(\frac{\partial\tilde{v}_{2+}}{\partial x} - \frac{k_{0}\tilde{E}_{0+}}{m_{e}\omega_{0}}\tilde{E}_{r+})$$

(32)

If we let $\tilde{v}_{2+} = v_{2+}^{*}(\hat{x} + i\hat{y})$ Fourier transformation of Eq. (2.62) then gives:

$$\tilde{v}_{2+} = \frac{e\tilde{E}_{0+}k_{0}\tilde{E}_{r+}}{m_{e}(\omega_{r}-\omega_{ce})}$$

(33)

where superscript * implies a complex conjugate of that quantity.

Where Laser velocity

$$\tilde{v}_{0+} = \frac{e\tilde{E}_{0+}}{m_{e}(\omega_{r}-\omega_{ce})}$$

(34)

The low frequency wave (THz) will be Right circular polarized wave. By substituting Eq. (33), (34) in Eq. (28) we get:

$$\tilde{f}_{2+} = \frac{-im_{e}e^{2}(\frac{\tilde{v}_{2+}}{m_{e}(\omega_{r}-\omega_{ce})})}{m_{e}(\omega_{r}-\omega_{ce})}(1 - \frac{\omega_{k_{1}}\omega_{k_{2}}}{\omega_{k_{1}}\omega_{k_{2}}})\tilde{E}_{r+}$$

(35)

In the above equation, contribution of the term to the nonlinear coupling coefficient is small and is, therefore, neglected. Combining Eq. (31) & (35) and substituting in (26), we obtain the following wave equation for $\tilde{E}_{r+}$ in terms of the electric fields of the pump and plasma wave.
**Impact Factor:**

| Journal          | Impact Factor |
|------------------|---------------|
| ISRA (India)     | 4.971         |
| ISI (Dubai, UAE) | 0.829         |
| PHHH (Russia)    | 0.126         |
| GIF (Australia)  | 0.564         |
| JIF              | 1.500         |
| SIS (USA)        | 0.912         |
| ISI (Dubai, UAE) | 0.829         |
| GIF (Australia)  | 0.564         |
| JIF              | 1.500         |
| ICV (Poland)     | 6.630         |
| PIF (India)      | 1.940         |
| IBI (India)      | 4.260         |
| OAJJ (USA)       | 0.350         |

**Figure (2)** Variation of beam width parameter \( f_{0+} \) along normalized distance \( \xi = z/R_0 \) for several values of initial plasma frequency \( \omega_{pe} \), in the Nonparaxial region.

**Figure (3)** illustrates the variations of the normalized THz field amplitude \( E_t/E_{00} \) along the normalized propagation distance \( \xi = z/R_0 \) in paraxial region, for several values of initial plasma frequency \( \omega_{pe} \).

We noticed that there is an insignificant increase in THz radiation amplitude with the increase in initial plasma frequency. Furthermore, the stability of THz radiation will be slow and less when the initial plasma frequency is increased. The oscillation pattern of THz amplitude is more regular and alternated in magnitude. That means the generated current conduct of THz is based on the density and thermal speed of electrons.

**Figure (3)** Variations of the normalized THz field amplitude \( E_t/E_{00} \) along normalized propagation distance \( \xi = z/R_0 \) with several values of initial plasma frequency \( \omega_{pe} \), in Nonparaxial region.

The increase of electronic density without increasing in its velocity (fixed intensity of laser beam), leads to the current increase, which in turn leads to the increasing stability of THz without increasing its amplitude. The THz radiation is affected by two opposite influences, the first refers to the fact that initial plasma frequency increase leads to self-focusing power that leads to increasing the amplitude and the stability of THz. The second influence affects THz radiation in the way that the initial plasma frequency increase leads to the decrease in THz frequency according to the relation of conserving the energy and momentum, and decrease of normalized ripple density amplitude \( \mu = \bar{n}_p/n_e \) according to the Eq. (2.66) which leads to decreasing the amplitude and stability of THz according to the previous studies.

**Conclusion**

At high enough intensity laser, a nonlinear pondermotive force will be created inside plasma leading to the self-focusing of laser beam. The self-focused laser beam will increase the laser beam...
intensity to high level enough to excite THz wave. The phase matching conditions between laser, plasma and THz waves should also be satisfied. The self-focusing in both regions (paraxial and nonparaxial) becomes faster and stronger when the initial Plasma frequency is increased. THz stability is reversely proportional with initial plasma frequency in both, paraxial and Nonparaxial regions without apparent high increase in its amplitude. The stability of THz is higher in non-paraxial than in paraxial region.

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