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GENERATION OF TERAHERTZ FIELD BY NONLINEAR INTERACTION BETWEEN LASER BEAM AND PLASMA

Abstract: *The study is a theoretical and simulator study of nonlinear ponderomotive force interaction between RCP laser beam TEM_{00} 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 radios 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 radios 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 both, paraxial and Nonparaxial regions without apparent high increase in its amplitude. 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. $\omega_0 = 1.778x10^{15}\ rad/s$. Initial plasma frequency. $\omega_1 = (0.8,0.84,0.88w_0)\ rad/s$. Applied magnetic field B_0=60 KG*

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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 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 $10\mu m$ spot size, can produce high intensity of the order $10^{21} W/cm^2$ at $1.06\mu m$ 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 ponderomotive 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. Self-focusing phenomena of (RCP) laser beam propagating through magneto-plasma at nonparaxial region & paraxial region is studied. The beam gets focused when the initial power of the laser beam is greater than its critical power. When the matching phase conditions are satisfied between the wave of ripple density plasma and electromagnetic laser wave and the frequency in THz range. Then, the result of beam focusing couples with the pre-existing density ripple of plasma will produce a nonlinear current driving the THz radiation.

Nonlinear Dielectric Constants in present of Longitudinal Magnetic Field:

Consider the propagation of a circularly polarized laser beam of angular frequency ω_o in a homogeneous magneto plasma with electronic density n_o, along the direction of static magnetic field $\vec{B}_0\hat{z}$. **Figure (1).**

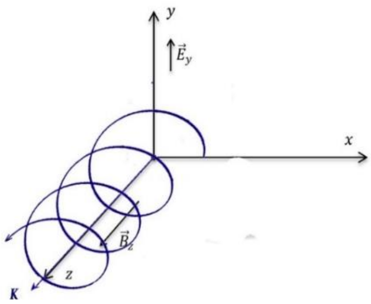

Figure (1) Draw Geometry of right circularly polarized laser beam mode of longitudinal magnetic field [1].

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]:

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

where $\vec{A}_{0+} = \vec{E}_x + i\vec{E}_y$ represents the electric field amplitude of (RCP) laser beam, ω_0 and k_{0+} are the angular n frequency and the wave vector respectively, ε_{0+} represents the dielectric constant in linear regime it is related with $k_{0+}^2 = \frac{\varepsilon_{0+}\omega_0^2}{c^2}$. c is the light velocity in the vacuum. The electron general motion equation in electromagnetic field is:

$$m_e \frac{\partial}{\partial t}\vec{\upsilon} = -e\vec{E}_{0+} - \frac{e}{c}(\vec{\upsilon} \times \vec{B}_o), \qquad (2)$$

Where $\vec{\upsilon}$ the oscillating velocity transmit by laser beam. e and m_e represent the charge and mass of electron respectively.

Where $\omega_{op} = \left(\frac{4\pi n_o e^2}{m_o}\right)^{\frac{1}{2}}$ is the plasma frequency.

We will use the laser beam fundamental mode (TEM_{00}) which is Gaussian profile intensity distribution.

laser beam (TEM_{00}) intensity will redistribute electronic plasma density n_o to become n_{e+} which will stimulate the ponderomotive force [3]:

$$n_{e+} = n_o \exp(-\alpha_+ A_{0+} A^*_{0+}) \qquad (3)$$

Where α_+ is the ponderomotive force nonlinearity parameter represent by the equation [4].

$$\alpha_+ = \frac{e^2(1-\frac{\omega_c}{2\omega_0})}{16 k_B m_e \omega_0^2 T_o (1-\frac{\omega_c}{\omega_0})^2} \qquad (4)$$

Where k_B and T_o 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]

$$\varepsilon_+ = \varepsilon_{xx} - i\varepsilon_{xy} = \varepsilon_{o+} + \varepsilon_{2+}(A_{o+}A^*_{o+}) \qquad (5)$$

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

$$\varepsilon_{0+} = 1 - \frac{\left(\frac{\omega_{pe}}{\omega_0}\right)^2}{\left(1-\frac{\omega_{ce}}{\omega_0}\right)} \qquad (6)$$

$\boldsymbol{\varepsilon_{2+}(A_{o+}A^*_{o+})}$ represents the nonlinear part, due to high intensity laser beam which is represented by the following equation [6]: -

$$\varepsilon_{2+}(A_{o+}A^*_{o+}) = \frac{\left(\frac{\omega_p}{\omega_0}\right)^2}{\left(1-\frac{\omega_c}{\omega_0}\right)}\left(1-\exp(-\alpha_+ A_{o+}A^*_{o+})\right) \qquad (7)$$

At low laser intensity the nonlinear part, of the effective dielectric constant $\boldsymbol{\varepsilon_{2+}}$ will approach to zero, because of $\boldsymbol{\alpha_+ A_{o+} A^*_{o+}}$ (the ponderomotive force) will approach to zero, the Influence of dielectric constant $\boldsymbol{\varepsilon_+}$ will approach to linear dielectric constant $\boldsymbol{\varepsilon_{o+}}$ [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 ε_{0+} will be modified to the effective dielectric constant ε_{+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 ε_{+eff} to understand the nonlinear behavior of laser beam in Nonparaxial region. [8].

$$\varepsilon_{+eff} = \varepsilon_{0+} + \varepsilon_{2+}A_{0+}A^*_{0+} = 1 - \frac{\left(\frac{\omega_{pe}}{\omega_0}\right)^2}{\left(1-\frac{\omega_{ce}}{\omega_0}\right)} + \frac{\left(\frac{\omega_{pe}}{\omega_0}\right)^2}{\left(1-\frac{\omega_{ce}}{\omega_0}\right)}\left(1 - e^{-\alpha_+ A_{0+}A^*_{0+}}\right) \qquad (8)$$

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

$$\nabla^2 \vec{E}_{0+} - \nabla(\vec{\nabla}\cdot\vec{E}_{0+}) + \frac{\omega_0{}^2}{c^2}\underline{\varepsilon}\cdot\vec{E}_{0+} = 0 \qquad (9)$$

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

And $\vec{A}_{0+} = \vec{E}_x + i\vec{E}_y$ represents the electric field amplitude of (RCP) laser beam, ω_0 and k_{0+} are the angular n frequency and the wave vector respectively, ε_{0+} represents the dielectric constant in linear regime it is related with $k^2_{0+} = \frac{\varepsilon_{0+}\omega_0^2}{c^2}$. c is the light velocity in the vacuum. Following Sodha et al. (1974b) method and using Eq. (8) so the general wave equation (9) can be written as [63].

$$\frac{\partial^2 A_{0+}}{\partial z^2} + \frac{1}{2}\left(1+\frac{\varepsilon_{0+}}{\varepsilon_{0zz}}\right)\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}\right)A_{0+} + \frac{\omega_0^2}{c^2}\left(\varepsilon_{0+}+\varepsilon_{2+}A_{0+}A^*_{0+}\right)A_{0+} = 0 \qquad (10)$$

The sound dravite four RCP laser beam amplitude (TEM_{00}), $\left(\frac{\partial^2 A_{0+}}{\partial x^2}, \frac{\partial^2 A_{0+}}{\partial y^2}\right)$ have been neglected.

Presenting $A_{0+} = A'_{0+}\exp i(\omega_0 t - k_{0+}z)$, where $A'_{0+} = A^o_{0+}\exp(ik_{o+}S_+)$, is a complex amplitude, A^o_{0+} and S_+ are a real function and the phase function of the laser beam through magnetized plasma respectively, therefore Eq.(10) can be written as [64].

$$2\frac{\partial S_+}{\partial z} + \frac{1}{2}\left(1+\frac{\varepsilon_{0+}}{\varepsilon_{0zz}}\right)\left(\frac{\partial S_+}{\partial x}\right)^2 - \frac{1}{2k^2_{0+}A^0_{0+}}\left(1+\frac{\varepsilon_{0+}}{\varepsilon_{0zz}}\right)\frac{\partial^2 A^0_{0+}}{\partial x^2} = \frac{\varepsilon_{2+}}{\varepsilon_{0+}}(A^0_{0+})^2 \qquad (11)$$

$$\frac{\partial (A^0_{0+})^2}{\partial z} + \frac{1}{2}(A^0_{0+})^2\left(1+\frac{\varepsilon_{0+}}{\varepsilon_{0zz}}\right)\frac{\partial^2 S_+}{\partial x^2} + \frac{1}{2}\left(1+\frac{\varepsilon_{0+}}{\varepsilon_{0zz}}\right)\frac{\partial S_+}{\partial x}\frac{\partial (A^0_{0+})^2}{\partial x} = 0 \qquad (12)$$

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

They are respectively represented as the follows [65].

$$A^2_{00+} = \frac{E^2_{00+}}{f^2_{0+}}\left(1+\frac{\alpha_{00}r^2}{r_0^2 f^2_{0+}}+\frac{\alpha_{02}r^4}{r^4 f^4_{0+}}\right)e^{\left(\frac{-r^2}{r_0^2 f^2_{0+}}\right)} \qquad (13)$$

$$S_+ = \frac{S_{00}}{r_0^2} + \frac{S_{02}r^4}{r_0^4} \qquad (14)$$

$$S_{00} = \frac{r^2}{\left(1+\frac{\varepsilon_{0+}}{\varepsilon_{0zz}}\right)f^2_{0+}}\frac{\partial f_{0+}}{\partial z} \qquad (15)$$

where f_{0+} is the beam width parameter so the dravite $\frac{\partial f_{0+}}{\partial z}$ represents the variation spot size in other word focusing and defocusing laser beam during its propagation inside plasma. α_{00} represents spherical deformation coefficient of second order. α_{02} represents spherical deformation coefficient of fourth order. α_{00}, α_{02} distinguish the Nonparaxial region contribution of the beam intensity.S_{00} represents the spherical curvature of the wavefront. S_{02} 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 order $r_0^2$and r_0^4 of the resulting equation, so the equations of beam width parameter f_{0+} and wavefront deformation from the spherical shape S_{02} . will be as follows:

$$\frac{d^2f_{0+}}{dz^2} = \frac{1}{4}\left(1+\frac{\varepsilon_{0+}}{\varepsilon_{ozz}}\right)^2 \frac{(1-2\alpha_{00}-3\alpha_{00}^2+8\alpha_{02})}{k_{0+}^2 r_0^4 f_{0+}^3} - \frac{(1-\varepsilon_{0+})}{2\varepsilon_{0+}}\left(1+\frac{\varepsilon_{0+}}{\varepsilon_{ozz}}\right)\left(\alpha_+ E_{00}^2 e^{-\alpha_+\frac{E_{00}^2}{f_{0+}^2}}\right)\frac{(1-\alpha_{00})}{r_0^2 f_{0+}^2} \quad (16)$$

We will rewrite the Eq. (16) in term of normalized propagation distance $\zeta = z/k_{0+}r_0^2$ where $k_{0+}r_0^2 = R_D$ which represents the diffraction length, To be more convenient for numerical programming.

$$\frac{d^2f_{0+}}{d\zeta^2} = \frac{1}{4}\left(1+\frac{\varepsilon_{0+}}{\varepsilon_{ozz}}\right)^2 \frac{(1-2\alpha_{00}-3\alpha_{00}^2+8\alpha_{02})}{f_{0+}^3} - \frac{(1-\varepsilon_{0+})}{2\varepsilon_{0+}}\left(1+\frac{\varepsilon_{0+}}{\varepsilon_{ozz}}\right)\left(\alpha_+ E_{00}^2 e^{-\alpha_+\frac{E_{00}^2}{f_{0+}^2}}\right)\frac{(1-\alpha_{00})R_D k_{0+}}{r_0^2 f_{0+}^2} \quad (17)$$

$$\frac{\partial S_{02}}{\partial z} = \frac{(1-\alpha_{00}+\alpha_{02})(1-\varepsilon_{0+})\left(\alpha_+ E_{00}^2 e^{-\alpha_+\frac{E_{00}^2}{f_{0+}^2}}\right)}{2\varepsilon_{0+} f_{0+}^6} - \frac{1}{2}\left(1+\frac{\varepsilon_{0+}}{\varepsilon_{ozz}}\right)\frac{(\alpha_{00}^2-7\alpha_{00}\alpha_{02}+\alpha_{00}^3-2\alpha_{02})}{2k_{0+}^2 r_0^6 f_{0+}^6} - \frac{4S_{02}}{f_{0+}}\frac{\partial f_{0+}}{\partial z} \quad (18)$$

Equations (17) & (18) are ruling and representing the nonlinear behavior of laser beam in Nonparaxial region through magnetized plasma. $k_{0+}^2 r_0^4 = R_{D0}$ which is represent the diffraction length so Eq (17) represents the laser beam spot size variation due to Sequence diffraction & self-focusing, the first and second terms on the right hand respectively.

To solve the equations (17) & (18) completely we will use eq. (14) to calculate the variation of the coefficients α_{00} , α_{02} along z-axis as follows:

$$\frac{\partial \alpha_{00}}{\partial z} = -\left(1+\frac{\varepsilon_{0+}}{\varepsilon_{ozz}}\right)\frac{8f_{0+}^2 S_{02}}{r_0^2} \quad (19)$$

$$\frac{\partial \alpha_{02}}{\partial z} = \left(1+\frac{\varepsilon_{0+}}{\varepsilon_{ozz}}\right)\left(\frac{4f_{0+}^2 S_{02}}{r_0^2} - \frac{12\alpha_{00}f_{0+}^2 S_{02}}{r_0^2}\right) \quad (20)$$

The numerical calculation of the equations (17), (18), (19) & (20) will be solve numerically to understand the nonlinear self-focusing behavior of (RCP) laser beam propagated through the magneto-plasma in the Nonparaxial region. This will lead to the next step which is Terahertz generating mechanism.

Terahertz generating mechanism:

THz radiation generation mechanism (E_{T+}, ω_t, k_t) depends on nonlinear interaction between the (RSP) high-power laser beam $(E_{0+}, \omega_0, k_{0+})$ and the density ripple plasma wave (E_1, ω_1, k_1) in collision-less magneto plasma. The ponderomotive force due to this interaction generates a nonlinear current at a difference frequency. If the appropriate phase matching conditions are satisfied and the difference frequencies of the laser beam and plasma ripple density in THz range we will get $\omega_t = \omega_0 - \omega_1$ $\vec{k}_t = \vec{k}_{0+} - \vec{k}_1$, then this difference frequency will be about THz frequency.

We set up the model equations For the RCP THz as follows.

$$\overrightarrow{E_{T+}} = \hat{r}E_{T+}\, exp\, i\,(\omega_t t - k_t z) \quad (21)$$

Where $\hat{r}E_{T+} = A_{t+}(x,y,z) = E_{tx} + iE_{ty}$ is the amplitude of the RCP THz radiation.

The equation (2.51) is the complex representation for the THz electric field, E_{T+} and the variation of electric field. For the right-(left) handed wave, we have $\hat{r} = \hat{x} + i\hat{y}$-($\hat{r} = \hat{x} - i\hat{y}$) with $\hat{x}$ and $\hat{y}$ being the unit vectors along the x and y directions, respectively.

In the field of the plasma wave (ω_1, k_1) the electric field $\overrightarrow{E_1}$ general equation Wave will be as the following:

$$\overrightarrow{E_1} = \hat{z}E_1\, exp\, i\,(\omega_1 t - k_1 z) \quad (22)$$

The electrons (plasma wave) oscillating velocity $v_1\hat{z}$ and the electron density perturbation $\widetilde{n_p}$ are related by the following equation:

$$\mu = \frac{\widetilde{n_p}}{n_e} = \frac{k_1}{\omega_1}v_1 \qquad \text{where } v_1 = -\frac{ieE_1}{m_e\omega_1}$$

μ are the normalized ripple density amplitude.

The general wave equation for electric field vector $\overrightarrow{E_{T+}}$ propagate through magneto plasma written as (Shukla & Sharma, 1982):

$$\nabla^2\vec{E}_{T+}^2 = \frac{4\pi}{c^2}\frac{\partial \vec{J}_{T+}}{\partial t} + \frac{1}{c^2}\frac{\partial^2 \vec{E}_{T+}}{\partial t^2} \quad (23)$$

where $\vec{J}_{T+} = \vec{J}_{1+} + \vec{J}_{2+}$ is the total current density vector in the presence of low frequency electric field $\overrightarrow{E_{T+}}$, where $\vec{J}_{1+}$ and $\vec{J}_{2+}$are the linear and nonlinear current densities, respectively.

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

$$\nabla\cdot(n_j\vec{v}_j) + \frac{\partial n_j}{\partial t} = 0 \quad (24)$$

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

$$m_e\frac{\partial \vec{v}_e}{\partial t} + m_e(\vec{v}_e\cdot\nabla)\vec{v}_e = -e\vec{E}_{T+} - \frac{e}{c}\vec{v}_e \times \overrightarrow{(B_0} + \vec{B}) \quad (25)$$

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.

$$\vec{J}_{T+} = \vec{J}_{1+} + \vec{J}_{2+} \quad (26)$$

where $\vec{J}_{T+}$ is the total current density vector in the presence of low frequency electric field $\overrightarrow{E_{T+}}$.

where $\vec{J}_{1+}$ and $\vec{J}_{2+}$are the linear and nonlinear current densities, respectively.

$$\vec{J}_{1+} = -en_0\vec{v}^e_{1+} + en_0\vec{v}^i_{1+} \qquad (27)$$

$$J_{2+} = -e\widetilde{n^*_p}\vec{v}_{0+} - en_0\vec{v}^e_{2+} \qquad (28)$$

In the above equation, e and $\widetilde{n^*_p}$ are charge and density perturbation of the electron, and n_0 is the background density, where $\vec{v}^e_{1+}, \vec{v}^i_{1+}$ represents the electron and ion linear velocities, which can be extracted by solving momentum equation (2.55):

$$\vec{v}^e_{1+} = \frac{ie\vec{E}_{T+}}{m_e(\omega_T - \omega_{ce})} \qquad (29)$$

The linear velocity for ion:

$$\vec{v}^i_{1+} = \frac{ie\vec{E}_{T+}}{m_i(\omega_T + \omega_{ce})} \qquad (30)$$

where $\omega_{ci} = eB_0/m_i c$ is the ion cyclotron frequency with the ion mass m_i.

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

$$\vec{J}_{1+} = -in_0e^2\left(\frac{\omega_T}{m_e(\omega_T - \omega_{ce})(\omega_T + \omega_{ce})}\right)\vec{E}_{T+} \qquad (31)$$

The nonlinear velocity $\vec{v}^e_{2+}$is produced by the beating of electron velocity $\vec{v}^e_{1+}$ in density ripple with the laser velocity $\vec{v}_{0+}$, and corresponding to the laser-frequency magnetic field $\vec{B}_0 = (c\vec{k}_{0+}/\omega_0) \times \vec{E}_{0+}$, $\vec{v}^e_{2+}$ is obtained by solving the following equation (Shukla &Sharma, 1982),

$$m_e\left(\frac{\partial}{\partial t}\vec{v}^e_{2+} + \omega_{ce}\vec{v}^e_{2+} \times \hat{z}\right) = -m_e v^*\left(\frac{\partial \overrightarrow{v_{0+}}}{\partial z} - \frac{e}{m_e}\frac{k_{0+}}{\omega_0}\vec{E}_{0+}\right) \cong -\frac{e\vec{E}_{0+}}{\omega_0}\frac{\omega_{ce}}{(\omega_0 - \omega_{ce})}k_{o+}v^*_1 \qquad (32)$$

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

$$\vec{v}_{2+} = \frac{-ie\vec{E}_{0+}\omega_{ce}k_{0+}v^*_1}{m_e\omega_0(\omega_0 - \omega_{ce})(\omega_T - \omega_{ce})} \qquad (33)$$

where superscript $*$ implies a complex conjugate of that quantity.

Where Laser velocity

$$\vec{v}_{0+} = \frac{ie\vec{E}_{0+}}{m_e(\omega_0 - \omega_{ce})} \qquad (34)$$

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

$$\vec{J}_{2+} = \frac{-in_0e^2}{m_e(\omega_0 - \omega_{ce})}\left(1 - \frac{\omega_1 k_{0+} + \omega_{ce}}{\omega_0 k_1 m_e(\omega_{ce} - \omega_T)}\right)\mu^*\vec{E}_{0+} \qquad (35)$$

In the above equation, contribution of the ion 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 $\vec{E}_{T+}$ in terms of the electric fields of the pump and plasma wave.

Laser beam with magnetized plasma and THz generation (at r =0).

$$\frac{d^2\vec{E}_{T+}}{dz^2} + \frac{\omega_T^2}{c^2}\left[1 - \frac{\omega_{pe}^2}{(\omega_T + \omega_{ci})(\omega_T - \omega_{ce})}\right]\vec{E}_{T+} = \frac{1}{2}\frac{\omega_T^2}{c^2}\frac{\omega_T}{(\omega_0 - \omega_{ce})}\mu^*\left[1 - \frac{\omega_1 k_{0+} + \omega_{ce}}{\omega_0 k_1(\omega_{ce} - \omega_T)}\right]E_{0+} \qquad (36)$$

To investigate the THz electric field $\vec{E}_{T+}$ involving in the nonparaxial region and paraxial region one may introduce the electric field E_{0+} involving of laser beam in nonparaxial region (see Eq.13).

Therefore the (Eq.36) rewrite as following:

For nonparaxial region

$$\frac{d^2\vec{E}_{T+}}{dz^2} + \frac{\omega_T^2}{c^2}\left[1 - \frac{\omega_{pe}^2}{(\omega_T + \omega_{ci})(\omega_T - \omega_{ce})}\right]\vec{E}_{T+} = \frac{1}{2}\frac{\omega_T^2}{c^2}\frac{\omega_T}{(\omega_0 - \omega_{ce})}\mu^*\left[1 - \frac{\omega_1 k_{0+} + \omega_{ce}}{\omega_0 k_1(\omega_{ce} - \omega_T)}\right]\frac{E_{00+}}{f_{0+}}\left(1 + \frac{\alpha_{00}r^2}{r_0^2 f_{0+}^2} + \frac{\alpha_{02}r^4}{r^4 f_{0+}^4}\right)^{\frac{1}{2}} e^{\left(\frac{-r^2}{2r_0^2 f_{0+}^2}\right)} \qquad (37)$$

Results and Discussion

Plasma frequency ω_{pe} is proportional with plasma density n_o according to the equation $\omega_{pe} = (4\pi n_o e^2/m_e)^{1/2}$, so we will studying the influence of plasma density by studying the influence of plasma frequency. It is the same behavior in paraxial region with less response to the change of Plasma frequency ω_{pe}. This is due to the intensity of laser in Nonparaxial region which is lesser than the intensity in paraxial region, and the ray is not parallel to the axis. According to the Eq. (2.34), we suppose that the influence of permittivity ε_{+eff} is proportional with plasma frequency ω_{pe}, which is proportional with S.F phenomena that is clear in **Figure (2). Figure (2)** illustrates laser beam self-focusing or beam width parameter (f_{0+}) variation behavior in the paraxial region with variable values of initial plasma frequency ω_{pe}, we note that S.F behavior is proportional with plasma frequency ω_{pe}. When plasma density increases the focusing will increase, and beam width parameter (f_{0+}) go deeper, this is due to, when plasma density (electrons) increase the nonlinear interaction will be larger, and that leads to the normalized ripple density amplitude $\mu = \widetilde{n_p}/n_e$ will be larger, so rising up the ponderomotive force, which leads to refractive index η will be larger in the canter which mean thicker concave lance.

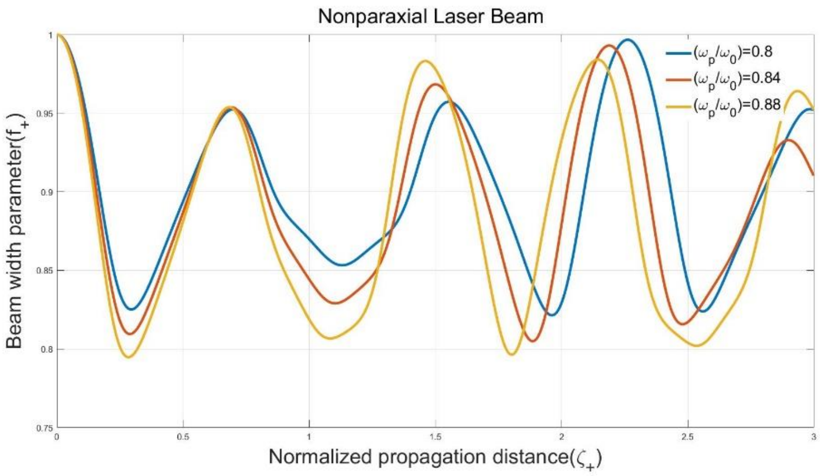

Figure (2) Variation of beam width parameter (f_{0+}) along normalized distance (ξ = z/R$_D$) for several values of initial plasma frequency (ω_{pe}), *in the Nonparaxial region.*

Figure (3) illustrates the variations of the normalized THz field amplitude E_t/E_{00} along the normalized propagation distance ξ = z/R$_D$ in paraxial region, for several values of initial plasma frequency ω_{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.

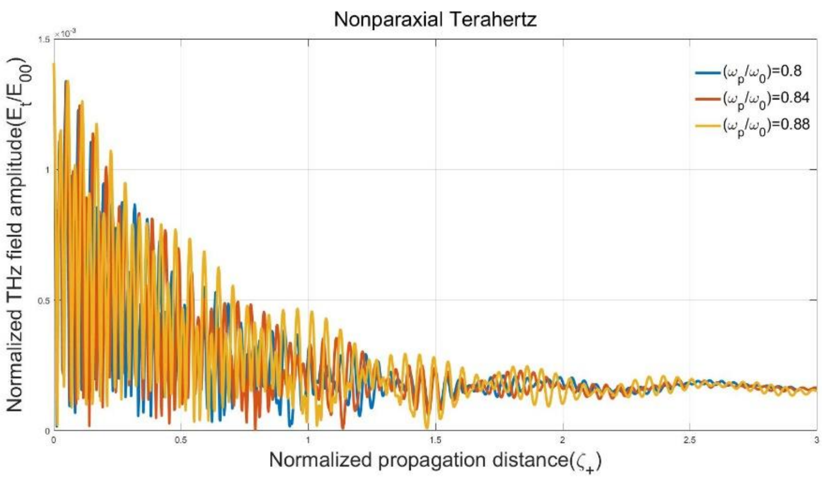

Figure (3) Variations of the normalized THz field amplitude (E_t/E_{00}) along normalized propagation distance (ξ = z/R$_D$) with several values of initial plasma frequency (ω_{pe}), *in Nonparaxial region.*

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 $\mu = \widetilde{n_p}/n_e$ 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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