Nonlinear Under dense Plasma by High Intensity Laser Pulse

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Abstract This research is studied the nonlinear interaction of underdense plasma by high intensity laser pulse regard to ohmic heating and effect of ponderomotive force. The nonlinear ponderomotive force was depended on particle oscillation in laser pulse that resulted to electron charge and electron density oscillation in plasma. The oscillation of heterogeneous electric field was imported to plasma electrons. Using the solutions of Maxwell's and hydrodynamic equations were investigated electron density, magnetic and electric field during plasma. Also Maxwell's equations were obtained through plasma and laser interaction by MATLAB programming language and fourth method of the Runge-Kutta. Based on results, increase of intensity of laser pulse was resulted to decrease of wavelength of magnetic and electric field. At the same time, oscillation of electron density was sharply peaked. Also temperature oscillation was increased and wavelength was decreased.

Keywords Nonlinear, Underdense plasma, High intensity laser pulse

1. Introduction

The production of high energy electron was considered in laboratory scale with high-power lasers as very active field of research [1-4]. Recently, the application of plasma was separated as new common method [5-6]. The acceleration of electron has important applications in various domains in the interaction of a high-intensity laser beam with plasma [7]. In underdense plasma, the propagation of high intensity laser pulse as many important researches caused to the relativistic plasma wave [8-14]. In last decade, the nonlinear interaction of high intensity laser was the subject of many important researches in underdense plasma [15-16].

Recently, the nonlinear propagation of intense laser pulse was studied through underdense magnetized plasma. The Maxwell equations were used to achieve the nonlinear equation for the electric field in plasma. The plasma wave is generated by the ponderomotive force (F_p) as a nonlinear force from regions of high intensity laser in an inhomogeneous oscillating electromagnetic. The equation of electron motion was taken into the average ponderomotive force per unit volume acting on the plasma electrons. Since the ion mass is much greater than the electron mass, the effect of the ponderomotive force was neglected on the ions [17]. Also, the ions motion and the nonlinear ohmic heating of the electrons were neglected in underdense collisional plasma by a laser pulse [18].

The effect of magnetic field was showed on waves in plasma [19-21]. The high magnetic field was played an essential role in particle transport, propagation of laser pulse, laser beam self-focusing, and penetration of laser radiation into over dense plasma. The plasma electron density was increased in the presence of the external magnetic field [17]. The effect of external magnetic field was characterized on electron density distribution and electromagnetic field in interaction of laser pulse with plasma [22-23]. The increase of laser intensity was caused the decrease of the wavelength of electric and magnetic field oscillations and the increase of the electron density, the oscillations amplitude of electron temperature, and the oscillations amplitude of the effective permittivity [18]. The collision of nonlinear electromagnetic plasma was created the nonlinear ohmic heating in plasma [24-25]. The plasma density and laser energy were affected on the stability of laser monoenergetic electron beam [7].

Theoretical studies of plasma wave propagation are importance for a vast range of problems. The Maxwell's equations were studied the collision effect in heating of underdense plasma by high intensity laser. The Maxwell’s and hydrodynamic equations were used for propagation of nonlinear wave in hot plasma [26]. The hydrodynamic equations were calculated electron density distribution and field profile in magnetized underdense plasma in theoretical section [27]. In the present work, the nonlinear interaction of high intensity laser pulse was studied with underdense plasma using Maxwell's and hydrodynamic equations. The changes were investigated for wavelength, intensity of laser pulse, density and temperature of electron, electric and magnetic field.

2. Theoretical Model and Formulation

The electron can be generated electric field in uniform filed of ion to protection neutral plasma. In this case, electrons were oscillated by specified frequency that called plasma frequency (ω_p). When magnetic field is zero (B=0), product of Boltzmann constant (k) and temperature (T) is zero (KT=0), ions are resident, plasma dimension is unlimited and electrons are moved in x-direction, ω_p is as follows:

$$\omega_p = \left(\frac{n_e e^2}{\varepsilon_0 m_e}\right)^{1/2} \quad (1)$$

Which n_e is electron density, e is electron charge, ε_0 is electric constant, and m_e is electron mass. The ponderomotive force is as follows:

$$F_p = 9\, \overline{n_e} \quad (2)$$

In the above equations, the plasma was depended on electron density. The interaction of laser with plasma has two general forms that depended on $(\frac{r_0}{C_s})$ function where r_0 and C_s are laser pulse and sound speed respectively [28]. If $\tau < \frac{r_0}{C_s}$ where τ is length of laser pulse, the laser radiation effect can be ignored on ions in plasma and ions were considered resident. The gas particles were ionized by laser pulse (Fig. 1), and caused ponderomotive force.

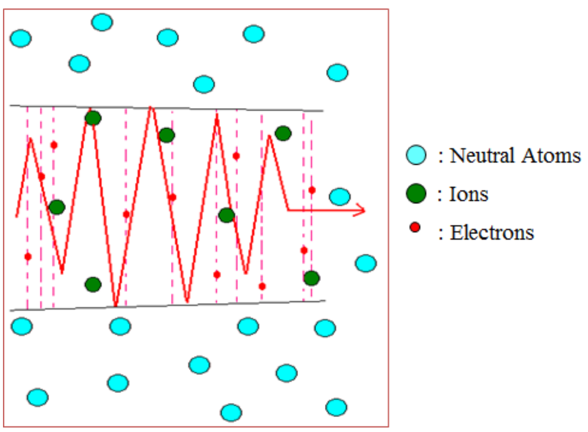

Figure 1. Schematic view of the ionized particles of gas by laser pulse

Hence, the ponderomotive force is as follows:

$$F_p = -\frac{m C^2}{2} \nabla a^2 \quad (3)$$

Which C is light velocity in weak field of one-dimensional. This force was resulted to particle oscillation and move electron in laser field. The effect of ponderomotive force on electron in unit volume is as follows:

$$F_p = -\frac{\omega_{pe}^2}{14 \pi \omega^2} \nabla E^2 \quad (4)$$

Which ω_{pe} is electron plasma frequency, ω is frequency, π is constant number and E is electric field. The relation of ponderomotive force for electron relative ion is as follows:

$$\frac{F_{pi}}{F_{pe}} = \frac{m_e}{m_{ii}} \quad (5)$$

Which F_{pi} and F_{pe} are ponderomotive force for ion and electron respectively. Also m_i is ion mass. Based on the result, the ponderomotive force had poor effect with larger electron mass. The electron density by considering potential (φ) and electron temperature (T_e) is as follows:

$$n_e = \exp\left(\frac{e\varphi}{T_e}\right) \quad (6)$$

When ω is electromagnetic wave frequency, electron density is $10^{20} \frac{g}{cm^3}$ and critical density (n_c) is $10^{21} \frac{g}{cm^3}$, and laser flux is in order of $I = 10^{17} \frac{W}{cm^2}$. According to the initial assumptions, parameter of focal point qatar (d) is 0.8 micrometer and laser pulse length 0.12 micrometer and radiation effects were ignored. The intensity of laser pulse was increased according to the formula $\frac{eA}{m_{oe} C^2} \cong 0.73$ where A is number vector potential and m_{oe} is base electron mass. Also, intensity of electromagnetic wave (P) is as follows:

$$P = \frac{15.89\, \omega^2}{\omega_{pe}^2} \quad (7)$$

The laser pulse was spread during Z direction in plasma. The nonlinear propagation was considered for high intensity laser pulse through collision of non-magnetic underdense plasma at the area Z> 0. Based on the assumptions, the ion is heavily and immovability in plasma. The geometry of coordinate system was shown for laser pulse in figure 2.

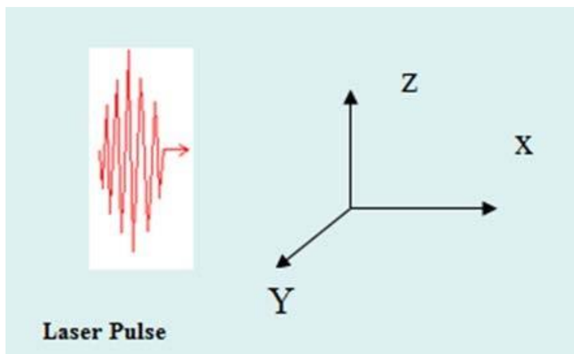

Figure 2. The geometry of coordinate system for laser pulse

In absence of any external current and charge, the Maxwell's equation is as follows:

$$\frac{\partial E_x}{\partial z} = \frac{i\omega}{C} B_y \quad (8)$$

$$\frac{\partial B_y}{\partial z} = \frac{i\omega}{C} \varepsilon E_x \quad (9)$$

$$\frac{d^2 E_x}{dz^2} + \left(\frac{\omega}{C}\right)^2 \varepsilon E_x = 0 \quad (10)$$

Which ε is dielectric constant coefficient. The electric field in plasma is as follows:

$$E_x(z,t) = E(z)\exp(-i\omega t) \quad (11)$$

The dispersion relation can be calculated as follows:

$$\nabla \times E = -\frac{1}{C}\frac{\partial B}{\partial t} \quad (12)$$

$$\nabla \times B = \frac{1}{C}\frac{\partial B}{\partial t} - \frac{4\pi}{C} e\, n_e V \quad (13)$$

Which V is electron speed and the amount of $\nabla \times E$ and $\nabla \times B$ were assumed zero as the result electron speed is zero in y and z direction for wave propagation in z direction. So $\nabla = -\frac{\partial}{\partial z}$ and $\frac{\partial}{\partial t} = -i\omega$.

$$-\frac{\partial B_y}{\partial z} = -\frac{i\,\omega}{C} E_x - \frac{4\pi}{C} e\, n_e V_x \quad (14)$$

Which E_x and B_y are electric filed in x direction and magnetic field in y direction respectively and V_x is electron speed in x direction. For electric field in plasma, differential equation is as follows:

$$-\frac{\partial^2 E_x}{\partial z^2} = -\frac{i\,\omega}{C}\frac{\partial B_y}{\partial z} \to \frac{\partial B_y}{\partial z} = -\frac{C}{i\,\omega}\frac{\partial^2 E_x}{dz^2} \quad (15)$$

$$\frac{C}{i\omega}\frac{\partial^2 E_x}{\partial z^2} = \frac{i\,\omega}{C} E_x - \frac{4\pi}{C} e\, n_e V_x \to \frac{\partial^2 E_x}{\partial z^2} + \frac{\omega^2}{C^2} E_x = \frac{4\pi i\omega}{C} e\, n_e V_x \quad (16)$$

In plasma collision, the equation of electron motion is as follows:

$$m_e n_e \left(\frac{\partial V_e}{\partial t} + (V_e.\nabla)V_e\right) = -e\, n_e E - e\, n_e \frac{V_e \times B}{C} - e\, n_e \nabla\emptyset - \nabla P_e \quad (17)$$

That $P_e = n_e T$ is electron pressure. The mean ponderomotive potential ($\emptyset$) is as follows:

$$\emptyset = E_x . A \quad (18)$$

Which oscillation domain of electron (A) is as follows:

$$\alpha_{max} = \frac{e\, E_x}{m_e\, \omega^2} \quad (19)$$

And the maximum of electron oscillation acceleration is as follows:

$$\alpha_{max} = A\omega^2 \to \frac{F}{m_e} = A\omega^2 \to \frac{e\,E}{m_e} = A\omega^2 \quad (20)$$

The ponderomotive force was affected on plasma electrons in unit of volume, so the overall relation is as follows:

$$F_{pe} = \frac{1}{4\pi} n_e \frac{\partial \varepsilon_{ij}}{\partial n_e} \nabla\left(E_i^* E_j\right) \quad (21)$$

That $F_{pe} = -e\, n_e \nabla \emptyset$ and $\varepsilon\varepsilon_{iiii}(\omega, k)$ is dielectric tensor that calculated for isotropic magnetic plasma. Using first order approximation, the motion equation is as follows:

$$m_e \frac{\partial V_x}{\partial t} = -e\, E_x \quad (22)$$

$$-\frac{e\, B_0 V_x}{C} - \frac{e\, \partial\emptyset}{\partial z} - \frac{1}{n_{0e}}\frac{\partial P_e}{\partial z} = 0 \quad (23)$$

Which B_0 is base magnetic field and n_{0e} is base electron density. When $\frac{\partial}{\partial t} = -i\omega$, V_x is as follows:

$$-m_e\, i\, \omega\, V_x = -e\, E_x \to V_x = \frac{eE_x}{i\,\omega\, m_e} \quad (24)$$

$$-\frac{e^2 B_0 E_x}{C\, i\, \omega\, m_e} - C\frac{\partial(e\, E_x^2 / m_e\, \omega^2)}{\partial z} = \frac{1}{n_{0e}}\frac{d(n_e T_e)}{dz} \quad (25)$$

$$-\frac{e^2 B_0 E_x z}{C\, i\, \omega\, m_e} - \frac{e^2 E_x^2}{m_e\, \omega^2} = T_e \ln\frac{n_e}{n_{0e}} \quad (26)$$

By division of the relation of 22 to electron temperature, the relation is as follows:

$$-\frac{e^2 B_0 E_x z}{C\, i\, \omega\, m_e T_e} - \frac{e^2 E_x^2}{m_e\, \omega^2 T_e} = \ln\frac{n_e}{n_{0e}} \quad (27)$$

$$-B_y = -\frac{i\,\omega}{C} E_x . z - \frac{4\pi}{C} e\, n_e V_x z \quad (28)$$

$$-B_y = -\frac{i\,\omega}{C} E_x . z - \frac{4\pi}{C} n_e \frac{e^2 E_x z}{i\,\omega\, m_e} \quad (29)$$

$$E_x . z = -B_y \left(\frac{C\, i\, m_e \omega}{m_e\omega^2 - 4\pi e^2 C\, n_e}\right) \quad (30)$$

That the amount of $4\pi e^2 C\, n_e$ is discarded, the relation is as follows:

$$E_x . z = -\frac{B_y\, C\, i\, m_e\, \omega}{m_e\, \omega^2} \quad (31)$$

By replacement relation of 31 to relation of 27, the relation is as follows:

$$-\frac{e^2 B_0 E_y\, C\, i\, m_e\, \omega}{C\, i\, \omega\, m_e T_e\, m_e \omega^2} - \frac{e^2 E_x^2}{m_e\, \omega^2 T_e} = \ln\frac{n_e}{n_{0e}} \quad (32)$$

$$\ln\frac{n_e}{n_{0e}} = -\frac{e^2 B_0 E_y}{m_e T_e\, \omega^2} - \frac{e^2 E_x^2}{m_e\, \omega^2 T_e} = \frac{e^2}{2\, m_e \omega^2 T_e}\left(E_x^2 - B_0 E_y\right) \quad (33)$$

$$n_e = n_{0e} \exp\left(\frac{e}{m_e \omega^2 T_e}\left(E_x^2 - B_0 E_y\right)\right) \quad (34)$$

The maximum of electron density is n_{0e} when magnetic and electric filed are zero ($E_x = B_y = 0$). Nonlinear differential equation of electromagnetic field in plasma is as follows:

$$\frac{\partial^2 E_x}{\partial z^2} + \frac{\omega^2}{C^2}\left(1 + \frac{4\pi e^2 n_{0e}}{m_e\, \omega^2} \exp\left(-\frac{e^2}{m_e \omega^2 T_e}\left(E_x^2 - B_0 E_y\right)\right) E_x\right) = 0 \quad (35)$$

The calculation of plasma conductivity coefficient is as follows:

$$\nabla \times \nabla \times E = -\frac{1}{C}\frac{\partial}{\partial t}(\nabla \times B) \quad (36)$$

$$\nabla(\nabla . E) - \nabla^2 E = -\frac{1}{C}\frac{\partial}{\partial t}(\nabla \times B) \quad (37)$$

By derivative from time, the relation is as follows:

$$\frac{\partial}{\partial t}(\nabla \times B) = \frac{1}{C}\frac{\partial^2 E}{\partial t^2}\left(-\frac{4\pi}{C}\frac{\partial J}{\partial t}\right) \quad (38)$$

That $\nabla . E = 4\pi\sigma$ and relation is as follows:

$$4\pi\nabla\sigma - \nabla^2 E + \frac{4\pi}{C^2}\frac{\partial J}{\partial t} - \frac{1}{C^2}\frac{\partial^2 E}{\partial t^2} = 0 \quad (39)$$

Which electron conductivity is σ. The electric constant is as follows:

$$\varepsilon = -\frac{K^2 C^2}{\omega^2} = 1 - \frac{\omega_{pe}^2}{\omega^2}\left(1 - \frac{\omega_c\, m_{0e}\, C^2}{\omega\, T_e}\right) \quad (40)$$

That $k = \frac{n\omega}{C}$ is cyclotron frequency and $\omega_c = \frac{e\, B0}{m_{0e} C}$ is refractive index of material. So $m_e C^2 = 0.5\, m_e V^2$, $T_e = 10Kev$ and $\omega_{pe} \geq\geq \omega$ and the change of ε is always positive.

$$\varepsilon = 1 - \frac{\omega_{pe}^2}{\omega^2}\left(1 - \frac{\omega_c\, m_{0e}\, C^2}{\omega\, T_e}\right) \quad (41)$$

The plasma is considered non-isothermal and collision is changed during laser radiation into plasma electron temperature. With regard to collisions, the result of electron vibrational motion is as follows:

$$v_x = \frac{e E_x}{i m_e \omega}\left(1 - \frac{i \nu_e}{\omega}\right) \quad (42)$$

The ohmic heating is produced in plasma therefore:

$$\frac{e E_x v_x}{2} = \frac{e^2 E^2 \nu_e}{2 m_e \omega^2} \quad (43)$$

By considering power of heating convection and collisions between electrons and natural particles, the equation is as follows:

$$-\nabla\cdot\left(\frac{\chi}{n}\nabla T_e\right) + \frac{3}{2}\delta \nu_{ei}(T_e - T_i) = \frac{e^2E^2\nu_{ei}}{2 m_e \omega^2} \quad (44)$$

There are $\frac{\chi}{n} = \frac{v_{th}}{\nu_e}$ and $v_{th}^2 = \frac{2 m_e}{m_{io}}$ where v_{th} is velocity of electron temperature. If the free mean time of electron is small, the first letter of left side is ignored and electron temperature is finally obtained as follows:

$$T_e = T_i + \frac{1}{3\delta}\left(\frac{e^2E^2}{m_e\omega^2}\right) \quad (45)$$

The hydrodynamic equation and the observation of semi-neutral circumstance are as follows:

$$\frac{-n_e e^2}{m_e \omega^2}\nabla E^2 = \nabla\left(n_e T_e + n_i T_i\right) \quad (46)$$

By replacing of electron temperature, plasma electron density, approximation study of semi-neutralize, and ion temperature of constant are as follows:

$$n_e = \frac{n_{0e}}{\left(1 + \frac{1}{6\delta T_i}\frac{e^2E^2}{m_e\omega^2}\right)^{1+3\delta}} \quad (47)$$

As a result, non-magnetic plasma of compact is excited by high intensity laser pulse for non-relativistic. The Maxwell's and hydrodynamic equation are as follows:

$$\frac{d^2E}{dz^2} + \left(\frac{\omega}{c}\right)^2\left[1 - \left(\frac{\omega_{peo}}{\omega}\right)^2 \frac{1}{\left(1+\frac{e^2E^2}{6\delta T_i m_e \omega^2}\right)^{1+3\delta}} \frac{1}{\left(1+\frac{i\nu_e}{\omega}\right)}\right]E = 0 \quad (48)$$

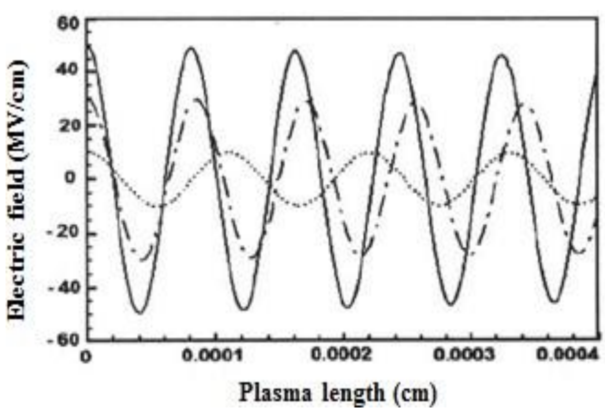

Figure 3. Changes in electric field as the function of plasma length (Z) for intensity of various laser pulses ($a/\sqrt{\delta\delta} = 1$: dotted line - $a/\sqrt{\delta} = 2$: bold dotted line - $a/\sqrt{\delta} = 4$: line)

The Maxwell's equations are obtained for interaction of laser and plasma using MATLAB programming language and Runge-Kutta method of fourth in right numbers and later. The change of electric field is shown as function of plasma length (Z) for intensity of various laser pulses (Fig. 3 and Fig. 4). Based on the result, the longitudinal section of electric field is increased by increasing of laser pulse intensity in plasma.

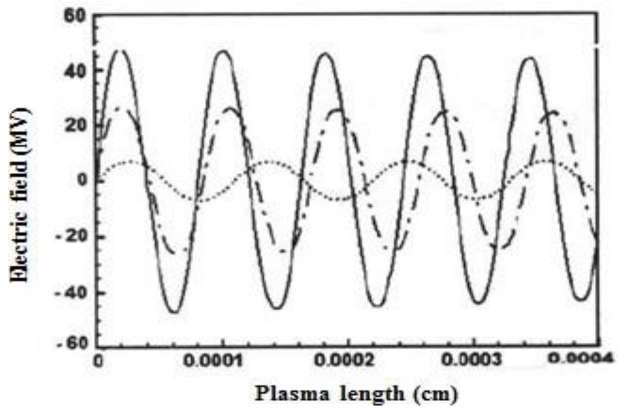

Figure 4. Changes in electric field as the function of plasma length (Z) for intensity of various laser pulses ($a/\sqrt{\delta\delta} = 1$: dotted line - $a/\sqrt{\delta} = 2$: bold dotted line - $a/\sqrt{\delta} = 4$: line)

The laser pulse intensity is as follows:

$I = 2.5 \times 10^{15}\ W/cm^2$

$I = 1.0 \times 10^{15} W/cm^2$

$I = 0.1 \times 10^{15} W/cm^2$

The critical density, base electron density and electron temperature are as follows:

$n_c = 1.7 \times 10^{21} cm^{-3}$

$n_{0e} = 1.0 \times 10^{21} cm^{-3}$

$T_e = 10$ Kev

The change of electron density ratio ($\frac{n_e}{n_{oe}}$) is shown as the function of plasma length (Z) for intensity of various laser pulses (Fig. 5). Based on the results, the oscillation of electron density is strongly increased by increasing of laser pulse intensity in plasma.

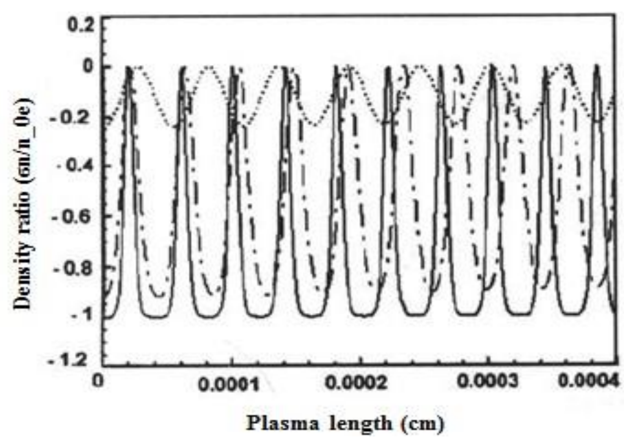

Figure 5. Changes in electron density ratio as the function of plasma length (Z) for intensity of various laser pulses ($a/\sqrt{\delta\delta} = 1$: dotted line - $a/\sqrt{\delta} = 2$: bold dotted line - $a/\sqrt{\delta} = 4$: line)

The laser pulse intensity is as follows:

$I = 2.5 \times 10^{15} W/cm^2$

$I = 1.0 \times 10^{15} W/cm^2$

$I = 0.1 \times 10^{15} W/cm^2$

The critical density, base electron density and electron temperature are as follows:

$n_c = 1.7 \times 10^{21} cm^{-3}$

$n_{0e} = 1.0 \times 10^{21} cm^{-3}$

$T_e = 10$ Kev

The change of electric field is shown as function of plasma length (Z) for various magnetic fields (Fig. 6). Based on the result, the wavelength oscillation of electric field is had little change by increasing of magnetic field in plasma.

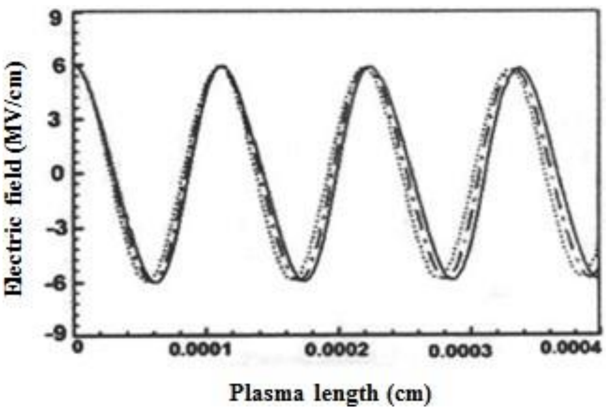

Figure 6. Changes in electric field as the function of plasma length (Z) for various magnetic fields ($a/\sqrt{\delta\delta} = 1$: dotted line - $a/\sqrt{\delta} = 2$: bold dotted line - $a/\sqrt{\delta} = 4$: line)

The laser pulse intensity is as follows:

$I = 2.5 \times 10^{15} W/cm^2$

The magnetic field is as follows:

$B_0 = 50$ MG

$B_0 = 20$ MG

$B_0 = 0$

The critical density, base electron density and electron temperature are as follows:

$n_c = 1.7 \times 10^{21} cm^{-3}$

$n_{0e} = 1.0 \times 10^{21} cm^{-3}$

$T_e = 10$ Kev

The change of magnetic field is shown as the function of plasma length (Z) for various magnetic fields (Fig. 7). Based on the result, the longitudinal section of magnetic field and the wavelength oscillation of magnetic field are increased a little in constant laser pulse intensity.

The intensity of laser pulse is as follows:

$I = 1.0 \times 10^{15} W/cm^2$

The magnetic field is as follows:

$B_0 = 50$ MG

$B_0 = 20$ MG

$B_0 = 0$

The critical density, base electron density and electron temperature are as follows:

$n_c = 1.7 \times 10^{21} cm^{-3}$

$n_{0e} = 1.0 \times 10^{21} cm^{-3}$

$T_e = 10$ Kev

The change of electron density ratio is shown as the function of plasma length (Z) for various magnetic fields (Fig. 8) and the oscillation of electron density is increased.

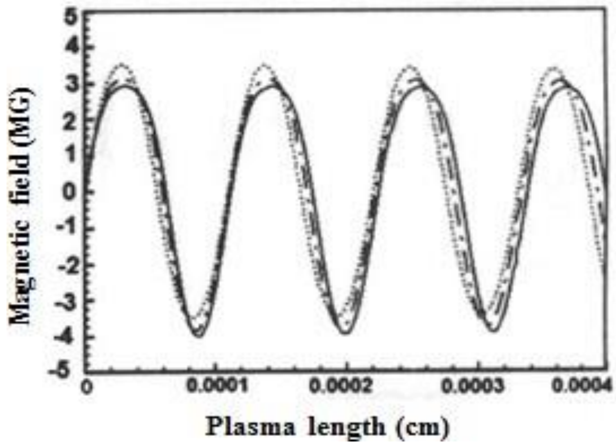

Figure 7. Changes in magnetic field as the function of plasma length (Z) for various magnetic fields ($\frac{a}{\sqrt{\delta}} = 1$: dotted line - $a/\sqrt{\delta} = 2$: bold dotted line - $a/\sqrt{\delta} = 4$: line)

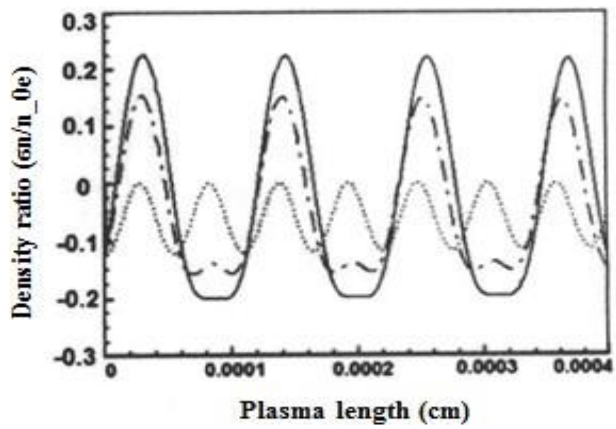

Figure 8. Changes in electron density ratio ($\frac{n_e}{n_{oe}}$) as the function of plasma length (Z) for various magnetic fields ($a/\sqrt{\delta\delta} = 1$: dotted line - $a/\sqrt{\delta} = 2$: bold dotted line - $a/\sqrt{\delta} = 4$: line)

The laser pulse intensity is as follows:

$I = 1.0 \times 10^{15} W/cm^2$

The magnetic field is as follows:

$B_0 = 50$ MG

$B_0 = 20$ MG

$B_0 = 0$

The critical density, base electron density and electron temperature are as follows:

$n_c = 1.7 \times 10^{21} cm^{-3}$

$n_{0e} = 1.0 \times 10^{21} cm^{-3}$

$T_e = 10$ Kev

The change of electric field is shown as the function of plasma length (Z) for various electron temperatures (Fig. 9) and the wavelength oscillation of electron temperature is decreased.

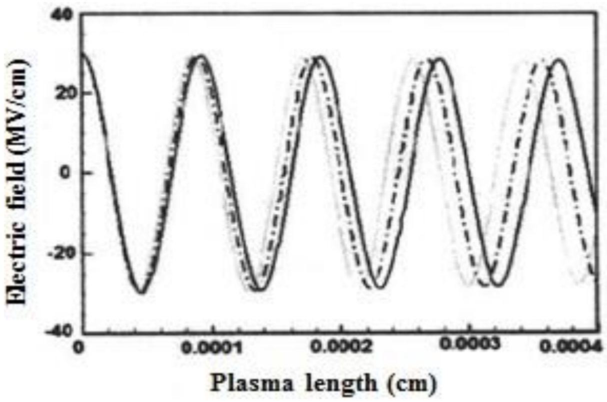

Figure 9. Changes in electric field as the function of plasma length (Z) for electron various temperatures ($a/\sqrt{\delta}\delta = 1$: dotted line - $a/\sqrt{\delta} = 2$: bold dotted line - $a/\sqrt{\delta} = 4$: line)

The laser pulse intensity is as follows:

$I = 1.0 \times 10^{15} W/cm^2$

The electron temperature is as follows:

$T_e = 20$ Kev

$T_e = 15$ Kev

$T_e = 10$ Kev

The critical density and base electron density are as follows:

$n_c = 1.7 \times 10^{21} cm^{-3}$

$n_{0e} = 1.0 \times 10^{21} cm^{-3}$

The change of electric field is shown as the function of plasma length (Z) (Fig. 10) and the oscillation of electric field is increased.

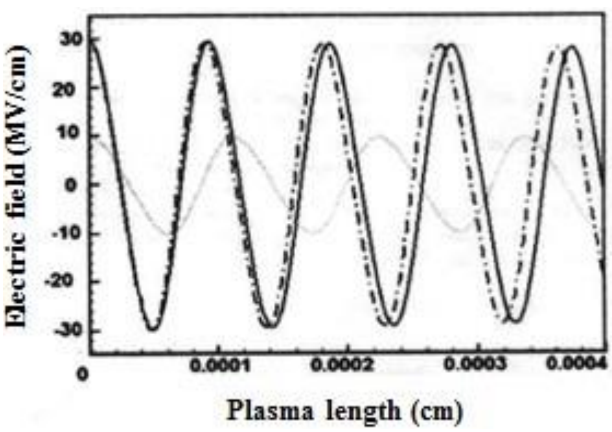

Figure 10. Changes in electric field as the function of plasma length (Z). ($a/\sqrt{\delta}\delta = 1$: dotted line - $a/\sqrt{\delta} = 2$: bold dotted line - $a/\sqrt{\delta} = 4$: line)

The magnetic field is as follows:

$$B_0 = 30 \text{ MG}$$

The change of magnetic field is shown as the function of plasma length (Z) for electron various temperatures (Fig. 11) and the longitudinal section of magnetic field and the ratio of effective magnetic field are increased.

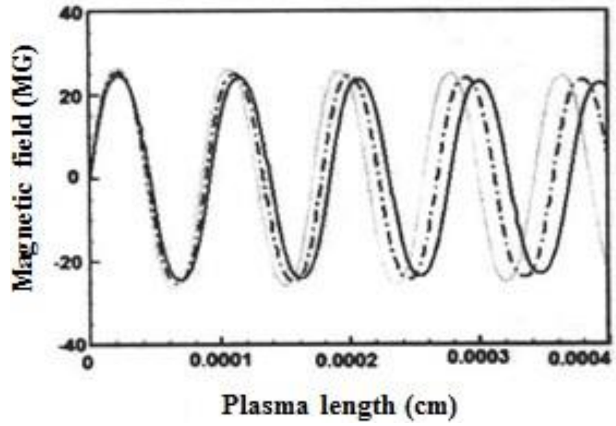

Figure 11. Changes in magnetic field as the function of plasma length (Z) for electron various temperatures ($\frac{a}{\sqrt{\delta}} = 1$: dotted line - $a/\sqrt{\delta} = 2$: bold dotted line - $a/\sqrt{\delta} = 4$: line)

The laser pulse intensity is as follows:

$I = 1.0 \times 10^{15} W/cm^2$

The electron temperature is as follows:

$T_e = 20$ Kev

$T_e = 15$ Kev

$T_e = 10$ Kev

The critical density and base electron density are as follows:

$n_c = 1.7 \times 10^{21} cm^{-3}$

$n_{0e} = 1.0 \times 10^{21} cm^{-3}$

The change of magnetic field is shown as the function of plasma length (Z) (Fig. 12) and the oscillation of magnetic field is increased.

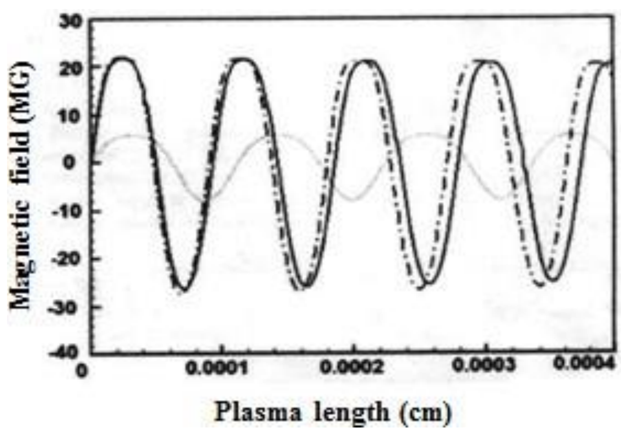

Figure 12. Changes in magnetic field as the function of plasma length (Z). ($\frac{a}{\sqrt{\delta}} = 1$: dotted line - $a/\sqrt{\delta} = 2$: bold dotted line - $a/\sqrt{\delta} = 4$: line)

The magnetic field is as follows:

$$B_0 = 30 \text{ MG}$$

The change of electron density ratio is shown as the function of plasma length (Z) for electron various temperatures (Fig. 13). Based on the result, the electron density is decreased since electric constant is increased.

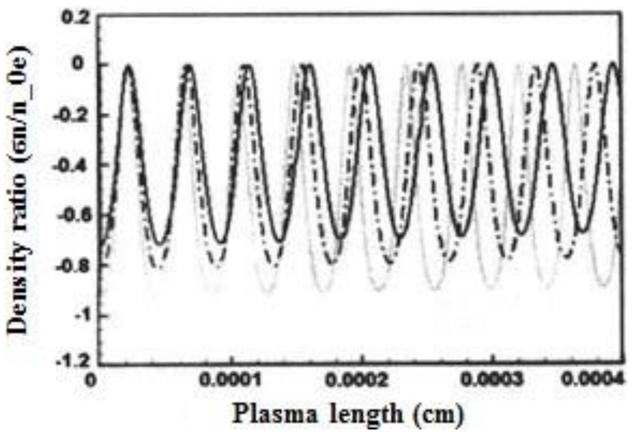

Figure 13. Changes in electron density ratio as the function of plasma length (Z) for electron various temperatures ($a/\sqrt{\delta\delta} = 1$: dotted line - $a/\sqrt{\delta} = 2$: bold dotted line - $a/\sqrt{\delta} = 4$: line)

The laser pulse intensity is as follows:

$I = 1.0 \times 10^{15} W/cm^2$

The electron temperature is as follows:

$T_e = 20$ Kev

$T_e = 15$ Kev

$T_e = 10$ Kev

The critical density and base electron density are as follows:

$n_c = 1.7 \times 10^{21} cm^{-3}$

$n_{0e} = 1.0 \times 10^{21} cm^{-3}$

3. Result and Discussion

The theoretical pattern was studied for interaction of underdense plasma. Based on the results, interaction of high intensity laser pulse is strongly nonlinear equation and there is no analytical solution. The fourth method of Runge-Kutta and MATLAB programming language were used to solve the equation in the numerical form. The interaction of high intensity laser pulse was decreased oscillation wavelength. The increase of laser pulse intensity was resulted to the increase of oscillation, the decrease of electron density, and the increase of electric constant. The oscillation wavelength of plasma was reduced by the decrease of electron density. And the electron wavelength was decreased by the increase of electric constant. The longitudinal section of field was shown nonlinear and non-sinusoidal because of the current increase of laser energy. The laser pulse intensity and electron density were increased as the function of plasma length along the z axis in images.

The laser pulse duration is greater than plasma thickness therefore the increase of dielectric constant is caused the decrease of electron density in plasma. This physical subject is increased size of magnetic and electric field oscillations. Also the changes of laser pulse intensity are caused the increase of electron density oscillations, temperature and magnetic influence. Based on the physical phenomenon, the created ohmic changes are caused the decrease of the electron wavelength that this subject is increased length section of magnetic electric and field for non-sinusoidal and nonlinear. In this article $\tau < \frac{r0}{C_s}$, and radiation effect of laser pulse is ignored on ions via consideration of created ohmic heating by the interaction of laser and plasma. The Maxwell's, hydrodynamics, energy equations are indicated that oscillation wavelength of electric field, wavelength of electron temperature oscillation domain and oscillation domain of magnetic influence is reduced.

4. Conclusions

In this study, high intensity laser interaction with underdense plasma was investigated by Maxwell's and hydrodynamic equations, ponderomotive force, electron ohmic heating, the longitudinal section in the electric and magnetic field, oscillation and density of electron. The oscillation wavelength of the longitudinal section was decreased and the oscillation was increased. The increase of intensity of laser pulse was strongly peaked the effective magnetic permeability, temperature and electron density oscillation because of the nonlinear ohmic heating effect. At same time, the wavelength was simultaneously decreased. In length section of electric and magnetic field, the oscillation wavelength was reduced but oscillation expansion was increased. The increase of intensity of laser pulse was dramatically increased density, temperature and effective magnetic permeability for electron in plasma. Also they were reduced because of the ohmic heating effect of the field.

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