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Al-Nahrain University
College of Science
Department of Physics

Study of Laser Acceleration of Electrons in a Magnetized Collisionless Plasma

A Thesis
Submitted to the Department of Physics, College of Science at
Al-Nahrain University in Partial Fulfillment of the Requirements
for the Degree of Master of Science in Physics

by

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Muhurram 1432 H **December 2010 AD**

بسم الله الرحمن الرحيم

"رب أوزعني أن أشكر نعمتك التي أنعمت علي وعلى والدي وأن أعمل صالحا ترضاه وأدخلني برحمتك في عبادك الصالحين"

صدق الله العظيم

سورة النمل
الاية 19

Dedication

To my parents

To my brothers

To my sisters and their husbands

with love and respect

Amal

Certification

We certify that this thesis was prepared under our supervision at Al-Nahrain university, College of Science, Department of Physics, in partial fulfillment of requirements for the degree of master of science (M.Sc.) in physics.

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Abstract

A theoretical and computational investigation was carried out in the field of laser-plasma interaction using the Finite Difference Method to study the acceleration of electrons with non-relativistic velocities in a non-magnetized and magnetized collisionless plasmas.

First, a (Nd:YAG) laser pulse of 25 fs duration and $5x10^{15}$ W/cm^2 intensity was assumed in the present study.
When this laser pulse was allowed to interact with a stationary electron in vacuum, it was found that the electron is accelerated during the interaction only and returns to stationary state after the laser pulse has passed, in agreement with previous works.

Also, the interaction of the same laser pulse with a collisionless plasma at electron density $n_e = 1x10^{18}$ cm^{-3} was studied. It was noticed that the energy of the electron during the interaction has reached a maximum value of ~ 1 keV at laser pulse intensity of $5x10^{15}$ W/cm^2, while the energy of the electron after the interaction reached ~ 15 eV for the same laser pulse intensity.

Finally, the interaction of the same laser pulse with a plasma was studied at electron density n_e=1x10^{18} cm^{-3} in the presence of an external magnetic field for the three values of the field strength B= 60 MG, 70 MG and 80 MG. It was found that there is an increase in the acceleration of the electron to reach a maximum energy of ~ 19 keV at a laser pulse intensity of 5x10^{15} W/cm^2 and an applied external magnetic field strength of 80 MG during the interaction. However, the electron energy after the interaction reached ~ 3 keV at a laser pulse intensity of 5x10^{15} W/cm^2 and an applied external magnetic field strength of 70 MG. This is due to a sustainable generated laser wakefield of ~ 2x10^9 V/cm. Thus, it is concluded that an applied external magnetic field assists the acceleration of the electron and can subsidize for a high laser beam intensity.

List of Symbols

symbol	meaning	unit
a (t)	acceleration of electron	cm/sec^2
a_x (t)	acceleration of electron in the x-direction	cm/sec^2
a_y (t)	acceleration of electron in the y-direction	cm/sec^2
a_o	unitless laser amplitude	-
B	magnetic field strength	Gauss
c	speed of light	cm/sec
e	electron charge	esu
E_k	kinetic energy of the electron	eV
E_o	maximum amplitude for electric field of laser pulse	V/cm
E_W	wakefield for an electron	V/cm
E_{W_x}	wakefield for an electron in the x-direction	V/cm
E_{W_y}	wakefield for an electron in the y-direction	V/cm
E_x	electric field for laser pulse in the x-direction	V/cm
F	Lorentz force	N
F_p	ponderomotive force for an electron	N
F_{p_x}	ponderomotive force for an electron in the x-direction	N
F_{p_y}	ponderomotive force for an electron in the y-direction	N
I	intensity of the laser pulse	W/cm^2
k	wave number	cm^{-1}
m_e	mass of the electron	gm
n_c	critical plasma density	cm^{-3}
n_e	number of electrons in a plasma per unit volume	cm^{-3}

R_L	Larmor radius	cm
s (t)	position of the electron	cm
t	time duration of the pulse	sec
T_f	fall time for the laser pulse	sec
T_{off}	time at which driving field is switched off	sec
T_r	rising time for the laser pulse	sec
v	velocity of electron	cm/sec
v_o	initial velocity of electron	cm/sec
$v_x(t)$	velocity of electron in the x-direction	cm/sec
$v_y(t)$	velocity of electron in the y-direction	cm/sec
x (t)	position of electron in the x-direction	cm
y (t)	position of electron in the y-direction	cm
β	Lorentz factor	-
δ	displacement of electron from its initial position in a plasma	cm
δ_x	displacement of electron from its initial position in a plasma in the x-direction	cm
ε_o	permittivity of free space	F/cm
λ_o	wave length of the laser pulse	cm
$\rho(t)$	displacement of electron from its initial position in a magnetized plasma	cm
ρ_x (t)	displacement of electron from its initial position in a magnetized plasma in the x-direction	cm
$\rho_y(t)$	displacement of electron from its initial position in a magnetized plasma in the y-direction	cm
ω	total frequency of the system	rad/sec
ω_c	cyclotron frequency of the electron	rad/sec
ω_o	laser frequency	rad/sec
ω_p	plasma frequency	rad/sec
Δt	time increment	sec

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Chapter One

Introduction

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Introduction

1-1 Particle accelerators

It is well known that particle accelerators are important tools in various fields such as particle physics, materials science, medical diagnostics and treatment, and manufacturing industry. However, further expansion of the utilization of conventional accelerators has become difficult because these accelerator facilities require large areas and huge financial resources [1].

An experimental laser-plasma accelerator at Lawrence Berkeley National Laboratory in the USA accelerates electrons to (1 GeV) requires (3.3 cm) space [2], whereas the SLAC conventional accelerator requires (64 m) length to reach the same energy [3]. A longitudinal electrostatic wave (wakefield) excited by a laser pulse in a plasma provides an acceleration field on the order of (100 GV/m) [1].

Therefore, a laser driven particle accelerator would provide the most promising approach to realizing high-performance compact accelerators [1].

The interaction of a laser pulse with a plasma can give rise to a large number of electrons from the accelerator in the plasma in the presence of an external magnetic field. This is due to the huge electric-field that can be sustained by carefully selecting the laser and plasma parameters which are possible to generate a mono energetic electron beam [1].

Plasma-based accelerators are used in many applications, such as high resolution radiography for non-destructive material inspection, radiotherapy, ultra fast chemistry, radiobiology and material science [1]. In addition, the interaction of laser pulse with a plasma can increase the electron density in the plasma [4].

Tajima and Dawson originally were the first to propose three decades ago laser-driven plasma based accelerators. Dawson was responsible for many of the early developments in this field, including the plasma beat wave accelerators, the laser wakefield accelerators, and the photon accelerator [5].

1-2 Basic concepts

A plasma is a quasi-neutral gas of charged and neutral particles, which exhibits collective behavior [6]. A plasma can be created in the laboratory in many ways, for example a plasma can be created from solids, liquids or gases by electrical discharge or by high power laser beam impinging on the material .When a high power laser pulse strikes a solid target, a sequence of energy conversion processes leads to the production of a hot and dense plasma [7]. A plasma can be described by several main important parameters such as plasma density, temperature of electrons and the degree of ionization [8].

Concepts for laser plasma –based accelerators, that illustrate in many ways the acceleration of electrons in a plasma, are:

1- A single short pulse of photons (so-called "Laser Wakefield Accelerator "LWFA):

In the laser wakefield accelerator a strong laser pulse propagating in a plasma generates the largest electric fields (wakefields) for acceleration of particles that can be produced by trapping electrons and ions in a plasma [9]. This is the type to be studied in the present work, as shown in Fig.(1-1).

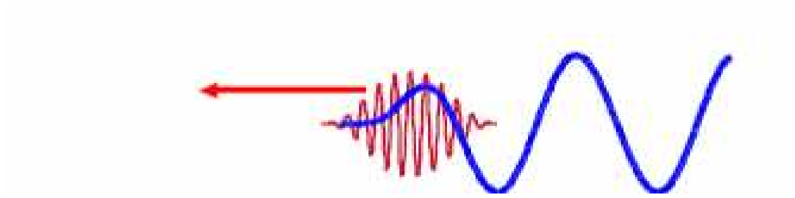

Figure (1-1) Plasma electron oscillation (blue line) as excited by a laser pulse (red line) in a plasma. The direction of propagation of a laser pulse is represented by the red arrow [10].

2- A train of pulses with fixed spacing (so-called "Plasma Beat Wave Accelerator" PBWA):

In a plasma beat wave accelerator two long laser pulses of frequencies ω_1 and ω_2 are used to resonantly excite a plasma wave. The large amplitude plasma waves can be generated when the laser frequencies and plasma frequency ω_p satisfy the resonance condition $\Delta\omega \equiv \omega_1 - \omega_2 \approx \omega_p$ [5], as shown in Fig.(1-2).

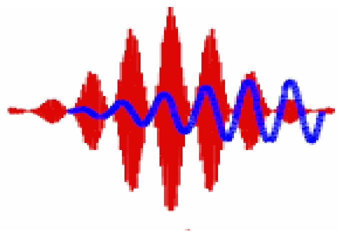

Figure (1-2) Plasma electron oscillations (blue line) as excited by a train of pulses (red line)in a plasma [10].

3- Raman forward scattering instability (so-called "Self Modulated Laser Wakefield Accelerator" SMLWFA):

The SMLWFA gives the best results for the acceleration of electrons. Its mechanism is rather complicated; it uses laser pulses which satisfy two requirements: first, the pulse width should be much longer than the plasma wavelength; second, its power should exceed the critical power of the relativistic self-focusing of the laser [11], as shown in Fig.(1-3).

Figure (1-3) Plasma electron oscillations (blue line) as excited by Raman forward scattering (red line) in a plasma [10].

4- A high energy electron (or positron) bunch (so-called "Plasma Wakefield Accelerator" PWFA):

As the driving electron beam enters a plasma, the plasma there sees an excess of negative charge to generate a plasma wakefield that results from the plasma electric field and the electric field for the electron beam and produces an acceleration of electrons in the plasma [12], as shown in Fig.(1-4).

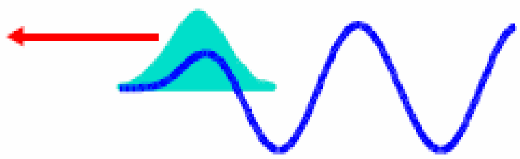

Figure (1-4) Plasma electron oscillations (blue line) as excited by an electron beam (green line) in a plasma medium, The direction of propagation is represented by the red arrow [10].

1-3 Previous works

Theoretical and experimental studies of the interaction of laser beams with plasmas have been attempted by many researchers.

In 1979, T. Tajima and J. M. Dawson [13] carried out a theoretical investigation to study laser electron acceleration through computer simulation using intense lasers of power density (10^{18} W/cm^2)shone on a plasma of density(10^{18} cm^{-3})

which can yield giga electron volts of electron energy per centimeter.

V. V. Apollonov et al. [14] in 1988, proposed a method for using focused laser light to accelerate electrons in a static transverse magnetic field and found a relationship between the magnetic field strength and the parameters of the laser beam.

In 1992, Y. Kitagawa et al. [15] observed acceleration of plasma electrons in the (PBWA) using two lines of a (CO_2) laser in a plasma of density (10^{17} cm^{-3}) and plasma electrons were trapped and accelerated to an energy in excess of (10 MeV).

K. Nakajima [16] observed electron acceleration to energies $\geq$ 18 MeV using a (3 TW),(1 ps),(10^{17} W/cm^2) laser pulse in a plasma of density near (10^{19} cm^{-3}) in 1995. In the same year, C. A. Coverdale et al. [17] observed electrons of (2 MeV) energy, which were trapped and accelerated from the background plasma when a (600 fs), (5 TW), ($8x10^{17}$ W/cm^2) laser pulse propagated in a plasma of density ($2x10^{19}$ cm^{-3}).

In 1996, C. J. Mckinstrie and E. A. Startser [18] studied the acceleration of an electron by a circularly polarized laser pulse in a plasma. It appeared possible to increase significantly the energy of a pre accelerated electron and generate the wakefield in the plasma.

In 1998, G. Brodin and J. Lundberg [19] investigated the interaction of a short one-dimensional weakly non-linear electromagnetic pulse with a plasma during general conditions.

The ion motion has been neglected and the frequency of the pulse was much larger than the plasma frequency in these investigations.

V. Petrzilka and L. Krlin [20] in 2002, demonstrated through numerical modeling that electrons can be accelerated in a single plane laser beam if an additional (secondary) perpendicularly propagating plane laser beam with a randomized phase is present and the additional laser beam can have a much lower power flux intensity than the main laser beam.

In 2003, H. Suk et al. [21] studied a laser wave passing through a sharp downward density transition in a plasma; a significant amount of plasma electrons were self-injected into the acceleration phase of the wakefield and accelerated to relativistic high energies over a very short distance. In the same year, D. Umstadter [22] presented an experimental investigation of the relativistic laser-plasma interactions. It has been established that by focusing peak power laser light to intensities up to (10^{21} W/cm^2), highly relativistic plasmas can be studied. The force exerted by light pulses with this extreme intensity has been used to accelerate beams of electrons and photons to energies of million volts.

P. Evans et al. [23] in 2004, carried out a theoretical investigation to study the characteristics of a plasma and the effect of the laser beam to best suit the plasma model behavior. In the same year, V. B. Krasovitskii et al. [24] investigated the interaction of an intense laser pulse propagating in a plasma in the presence of an external magnetic field to generate an electrostatic wakefield and electron acceleration in this field.

In 2009, S. Elizer and K. Mima [25] studied the interaction of a laser pulse with electrons and found no acceleration of electrons after the interaction, while in interaction of a laser pulse with a plasma using the particle-in-cell (PIC) technique, they observed the acceleration of electrons and the generation of a strong oscillating electrostatic field in its wake (wakefield) much in the same manner as a boat generates a wake when it travels through water.

1-4 Aim of the present work

The study in this thesis is carried out to investigate numerically the effects of a laser beam on the acceleration of electrons in vacuum and in a homogenous non-magnetized and magnetized collisionless plasmas, using the Finite Difference Method with different values of the external magnetic field applied on the plasma.

To this end, the rest of the thesis is organized as follows:

Chapter two introduces the theoretical basis of laser and plasma parameters, the equations that are used to study the acceleration of electrons and how a wakefield is generated.

Chapter three is devoted to the description of the computer programs that are used to study the acceleration of the electrons using the equations in chapter two.

Chapter four is a presentation of the results of this study together with their discussion and comparison with results of other studies in this field.

Finally, chapter five gives the main conclusions from this study together with suggestions for future work.

Chapter Two

Theoretical Considerations

Chapter Two

Theoretical Considerations

2-1 Laser parameters

The laser can be described by many parameters, the most important parameters are:

2-1-1 Unitless laser amplitude

To characterize the laser intensity, the dimensionless laser amplitude a_o is introduced [26].

An electron oscillating in the transverse electric field of an electromagnetic wave attains a maximum velocity $v_\perp$ given by [6]:

$$v_\perp = \frac{e\,E_x}{m_e\,\omega_o} \qquad (2-1)$$

where,

e is the electron charge

E_x is the electric field of laser beam in the x-direction

m_e is the electron mass

ω_o is the angular frequency of the laser beam

In addition, the unitless laser amplitude is defined as [26]:

$$a_o = \frac{v_\perp}{c} = \sqrt{\frac{e^2\,I\,\lambda^2}{2\,\pi^2\,c^5\,\varepsilon_o\,m_e^2}} \qquad (2-2)$$

or,

$$a_o = 8.65x10^{-10}\,\lambda\,(\mu m)\,I^{1/2}\,\left(W/cm^2\right) \qquad (2-3)$$

where,

I is the intensity of the laser beam

λ is the wavelength of the laser beam

ε_o is the permittivity of free space

c is the speed of light

The parameter a_o is very important for distinguishing the relativistic region where $a_o > 1$ from the non-relativistic region, which is the subject of the present work, where $a_o < 1$ [5].

2-1-2 The shape of the laser pulse

It is known that the time dependence of the field harmonic (sinusoidal) of a plane electromagnetic wave is given by [26]:

$$\vec{E}\,(r,t) = E_o\, e^{i\left(\vec{k}\,.\vec{r}-\omega_o\, t\right)} \qquad (2-4)$$

where,

k is the wave number

ω_o is the angular frequency of the laser beam

E_o is the maximum amplitude of the electric field of the wave

The maximum amplitude of the electric field of the wave can be calculated from [25]:

$$E_o = \frac{2\,\pi\, m_e\, c^2\, a_o}{e\,\lambda} \qquad (2-5)$$

2-2 Plasma parameters

The plasma can be described by many parameters, the most important parameters that used in the present work are:

2-2-1 Plasma frequency

In a plasma, the charged particles motion is governed by electrical forces. For example, electrons in a plasma repel each other or get displaced from ions and, therefore, begin to move apart. The electric field build up so that electrons are returned to their original positions. In this process, the electrons have gained momentum so that they keep on going and create a deficiency of negative charge which attracts the electrons back in. In time, the motion is reversed and a systematic oscillation of the charged region is setup. The oscillation of electrons around their equilibrium positions takes place with a characteristic frequency known as the plasma frequency and is given by [6,27]:

$$\omega_p = \left(\frac{4\,\pi\, n_e\, e^2}{m_e}\right)^{1/2} \qquad (2-6)$$

The ions are much heavier than the electrons; their motion is small enough and can be neglected [6].

2-2-2 Critical density, underdense and overdense plasmas

At the critical density, the laser beam cannot propagate into the plasma any more but decreases exponentially. For a given angular laser frequency, ω_o, and wavelength, λ, the cut-off takes place at the critical density, n_c, [28], where:

$$\omega_p = \omega_o$$

$$n_c = \frac{\omega_o^2 \, m_e}{4 \pi e^2}$$

$$\therefore \; n_c \left(cm^{-3}\right) = \frac{1.1x10^{21}}{\lambda^2 \left(\mu \, m\right)} \qquad (2-7)$$

This critical density defines the regimes of underdense and overdense plasmas.

The plasma frequency, ω_p, marks a fundamental boundary between conducting (underdense plasma) and dielectric (overdense plasma) behavior in the interaction of electromagnetic wave (laser beam) with a plasma [28].

When the incident laser frequency is larger than the plasma frequency, i.e.,

$$\omega_o > \omega_p$$

then

$$n_e < n_c$$

In this case the electrons respond to the incident field, resulting in transparency to the radiation from the so-called underdense plasma (under critical) [28], which is assumed in the present work.

When the incident laser frequency is less than the plasma frequency, i.e.,

$$\omega_o < \omega_p$$

then

$$n_e > n_c$$

In this case the electrons can respond and exclude the incident field, resulting in a reflection of wave energy from the so-called overdense (over critical) plasma as shown in Fig.(2-1) [28].

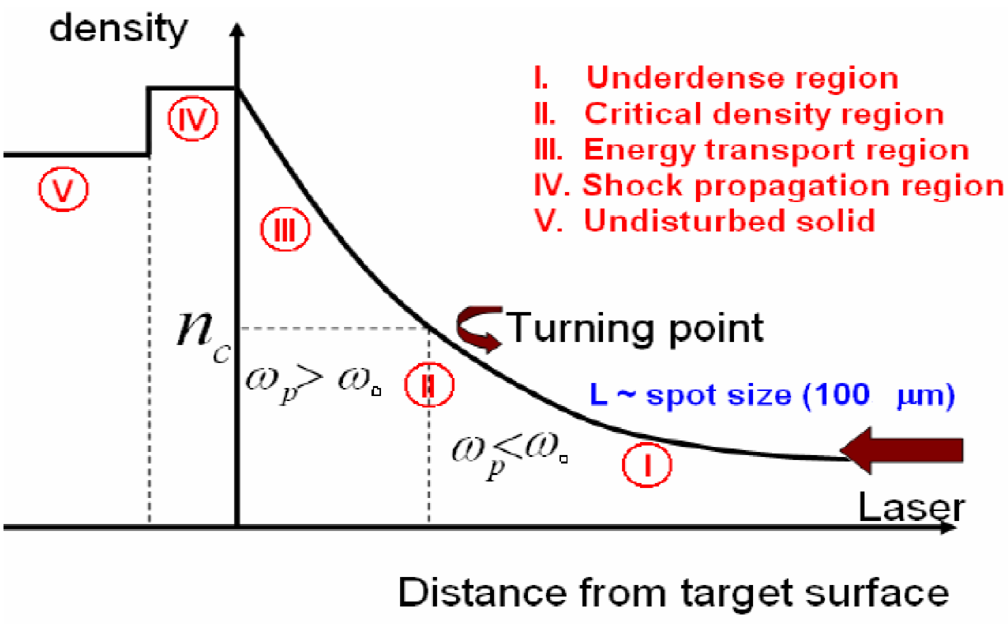

Figure (2-1) The regions of laser-plasma interactions [29].

2-3 Larmor radius

If a magnetic field is applied on charged particles, there are two forces produced (the magnetic force and centrifugal force) [30].Under these two forces the charge particles will move with a circular orbit which has radius known as "Larmor radius" as shown in Fig.(2-2).The Larmor radius is given by [6]:

$$R_L = \frac{m_e\, v_\perp\, c}{e\, B} \qquad (2-8)$$

The relation between kinetic energy of an electron and its Larmor radius is given by [31]:

$$R_L = \frac{(2\, m_e\, E_k)^{1/2}\, c}{e\, B} \qquad (2-9)$$

where E_k is the kinetic energy of the electron.

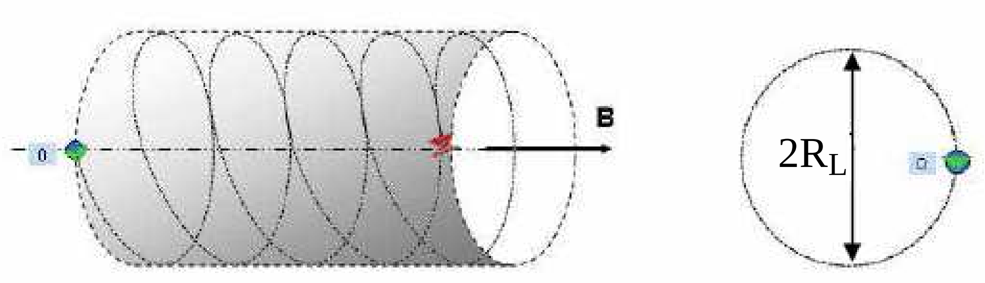

Figure (2-2) Motion of an electron showing the Larmor radius in a constant magnetic field [31].

In the absence of collisions, the electric field constantly increases the electron velocity and consequently its kinetic energy also increases [31].

The motion of the charged particle in a magnetic field is a simple harmonic motion with a frequency known as "cyclotron frequency" as shown in Fig.(2-3). The cyclotron frequency is given by [6]:

$$\omega_c = \frac{e\,B}{m_e\,c} \qquad (2-10)$$

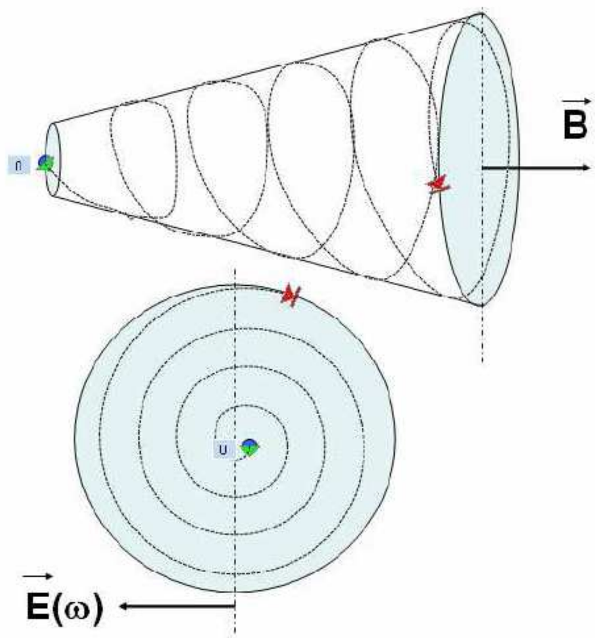

Figure (2-3) Trajectory of an electron in a magnetic field and the resulting increase in the Larmor radius [31].

Figure (2-3) illustrates this motion; when the radius increases and the cyclotron frequency remains constant, the velocity of electrons should increase to make a complete turn for each period.

2-4 Laser acceleration of electrons in vacuum

When a laser pulse interacts with electrons, it accelerates the electrons based on the Lorentz equation given by [25]:

$$\vec{F} = e\left(\vec{E}(t) + \vec{v} \text{ x } \vec{B}\right) \qquad (2-11)$$

where,

$\vec{E}(t)$ is the electric field of the laser pulse

$\vec{v}$ is the velocity of electron

$\vec{B}$ is the static magnetic field

For non-relativistic electrons, as in the present work, the magnetic force is smaller than the electric force. Therefore, the second term in eq.(2-11) involving the static magnetic field can be ignored and one gets [32]:

$$m_e\, \vec{a}(t) = e\, \vec{E}(t) \qquad (2-12)$$

For the numerical integration, setting on the acceleration $\vec{a}(t)$ of the electron in a given small time interval (Δt), the velocity of the electron is then determined by:

$$\vec{v}(t+\Delta t)=\vec{v}(t)+\vec{a}(t)\,\Delta t \qquad (2-13)$$

The position of the electron is determined by integrating eq.(2-13) with respect to (Δt), then:

$$\vec{s}(t)=\vec{v}(t)\,\Delta t+\frac{1}{2}\,\vec{a}(t)\,\Delta t^{2} \qquad (2-14)$$

where $\vec{s}(t)$ is the position vector of the electron after time t. The laser acceleration of an electron in vacuum is illustrated in Fig.(2-4) [33].

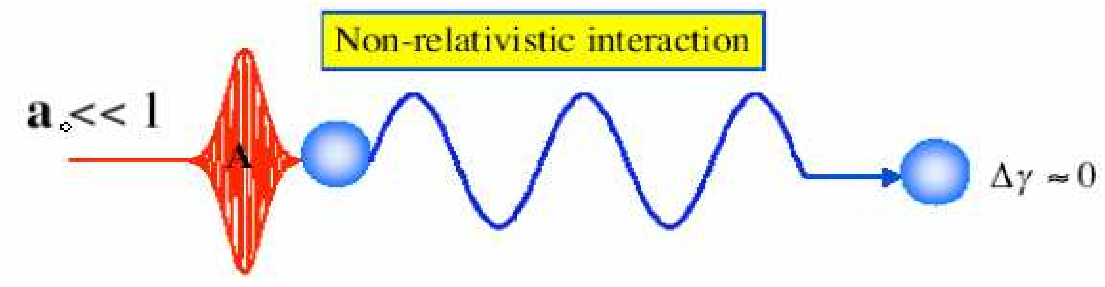

Figure (2-4) Laser acceleration of an electron in vacuum [33].

In this figure, the interaction of a laser pulse (red line) that has the maximum amplitude $A_{\perp}$ as a function of the unitless laser amplitude $a_{o}=\dfrac{e\,A_{\perp}\,\lambda}{2\pi m_{e}\,c^{2}}$ with a rest electron (blue ball),is illustrated. It can be noticed that the oscillation of an electron (blue line) takes place during the interaction, but after the interaction the electron returns to stationary state. Therefore, $\Delta\gamma=0$ where $\Delta\gamma = \dfrac{\Delta W}{m\,c^2}$ for the energy gain ΔW.

(where $\Delta\gamma$ is the ratio between the energy gain and the energy of electron).

2-5 Interaction of laser pulse with a plasma

A short laser pulse interacting with a plasma generates a strong oscillating electrostatic field much in the same manner as a boat generates a wake when it travels through water [25]. The force on the non-relativistic electron in the plasma includes the Lorentz force in addition to the force that results from the oscillation of the electron in the plasma.

The acceleration of a non-relativistic electron in the plasma is given by [34]:

$$\vec{a}(t) = \frac{e}{m_e}\vec{E}(t) - \omega_p^2\,\delta \qquad (2\text{-}15)$$

where δ is the displacement of the electron in the plasma. Further details of eq. (2-15) are illustrated in Appendix (A). By numerical integration of eq. (2-15), one finds the velocity, position and energy for the non-relativistic electron. The interaction of a laser pulse with a plasma is illustrated in Fig.(2-5) [33]:

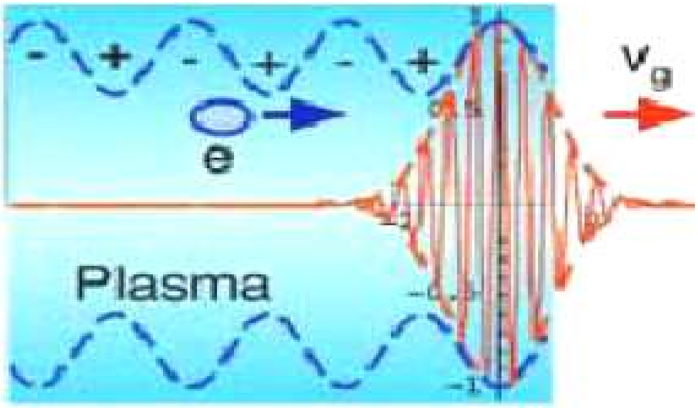

Figure (2-5) The interaction of a laser pulse with a plasma [33].

This figure illustrates the interaction of a laser pulse (red line) with an electron in a plasma, showing the oscillation of the electron after the interaction (dashed blue line) and the red arrow represents the direction of propagation of group velocity.

2-6 Interaction of a laser pulse with a magnetized plasma

A laser pulse propagating in a plasma in the presence of an external magnetic field can generate an electrostatic wakefield resulting in electron acceleration in the plasma [24]. The forces on an electron in a plasma subject to external electric and magnetic fields, $\vec{E}(t)$ and $\vec{B}$, one perpendicular to the other, result from the Lorentz force and the oscillation force after the displacement of the electron from its initial position. The displacement of an electron is given by:

$$\vec{\rho}(t) = \vec{s}(t)\left(1 - \frac{R_L}{|r|}\right) \qquad (2-16)$$

where $\vec{s}(t)$ is the position vector of the electron after time t. Further details of eq. (2-16) are illustrated in Appendix (B). The acceleration of a non-relativistic electron in a magnetized plasma is given by [34]:

$$\vec{a}(t) = \frac{e}{m_e}\vec{E}(t) + \omega_c\,\vec{v}(t) - \omega_p^2\,\vec{\rho}(t) \qquad (2-17)$$

The electric field is in the x-direction, while the magnetic field is in the z-direction.

By numerical integration of eq.(2-17), the velocity, position and energy of the electron can be found.

2-7 Electromagnetic waves in a magnetized plasma

When an electromagnetic wave propagates in a magnetized plasma perpendicular to an external magnetic field $\vec{B}$ applied on the plasma, and if the polarization of the electric field vector of the wave is parallel to $\vec{B}$, then the wave is called "the ordinary wave" because the plasma particles can move freely along $\vec{B}$ as they are accelerated by the electric field, and the magnetic field has no effect [35].But when the electromagnetic wave propagates in a magnetized plasma perpendicular to the magnetic field $\vec{B}$ that is applied on a plasma and the polarization of the electric field of the wave is also perpendicular to the magnetic field $\vec{B}$, then this wave is called "the extraordinary wave". Here, the electric field drives electron motion perpendicular to $\vec{B}$ and the magnetic force has effect on it [35].

In the present work, the effect of the extraordinary wave is utilized for the acceleration of the electron, where the electric field is in the x-direction and the external magnetic field applied on the plasma is in the z-direction as shown in Fig.(2-6):

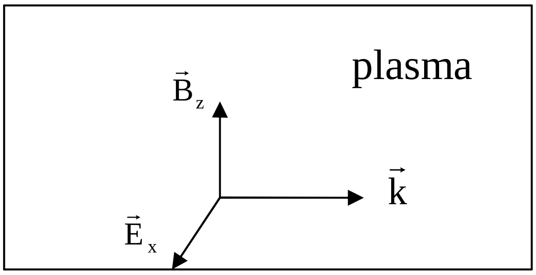

Figure (2-6) The $\vec{E}$-vector of an extraordinary wave is in the x-direction, $\vec{B}$-vector of an external magnetic field applied on a plasma is in the z-direction and $\vec{k}$-vector represents the direction of propagation of the wave in a plasma.

The dispersion relation for the extraordinary wave is given by [35]:

$$\omega^2 = c^2 k^2 + \omega_p^2 \left(\frac{\omega^2 - \omega_p^2}{\omega^2 - \omega_c^2} \right) \qquad (2-18)$$

One notes that for $\omega >> \omega_p$, ω_c ; the dispersion relation for the extraordinary wave becomes [35]:

$$\omega = c\,k \qquad (2-19)$$

2-8 Mechanism and theory of wakefield generation

In a plasma, the wakefield can be generated by injection of an electron beam or laser beam in a plasma region. The mechanism for generating the wakes is by exciting the electrostatic wave of the plasma behind the electron or laser beam [36,37]. This can be done by losing energy from the beam to the background plasma. When a laser beam propagates in an underdense plasma, plasma electrons are pushed out due to the ponderomotive force [13,38]. The density perturbation causes a plasma wave and the wave propagates at the speed of the laser beam [38]. The laser beam sets the electrons into oscillations with a net gain of energy in the region behind the beam. The laser beam can trap electrons and execute trapping oscillations and thus can gain energy. The electrons gain an amount of energy along the beam and suffer acceleration with increased plasma density [38]. The mechanism of wakefield generation is illustrated in Fig.(2-7) [29].

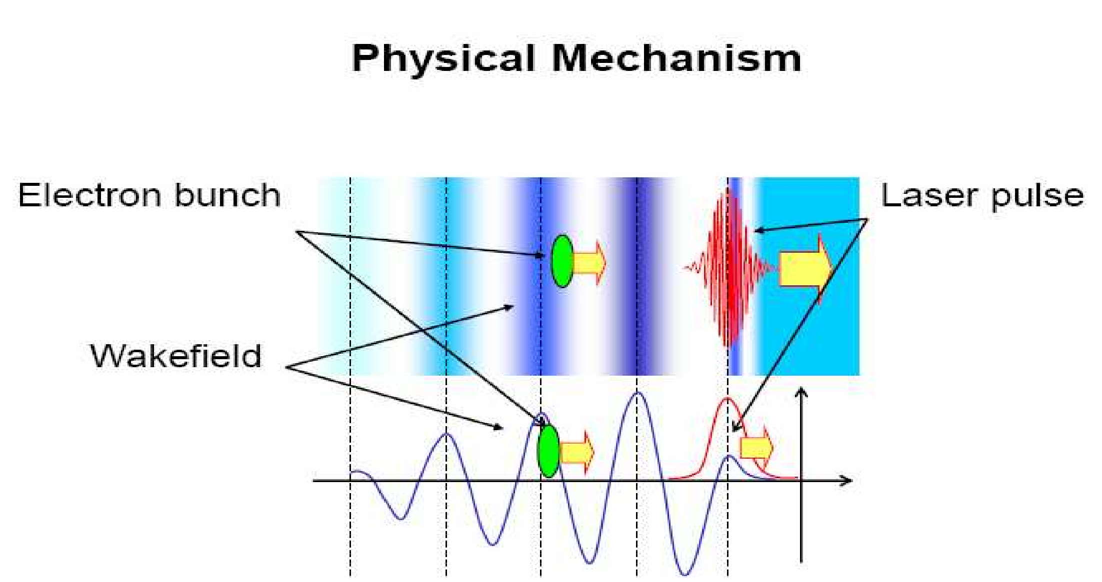

Figure (2-7) The physical mechanism of generation of wakefield [29].

The ponderomotive force and wakefield of an electron in a plasma are illustrated in Fig.(2-8) [39].

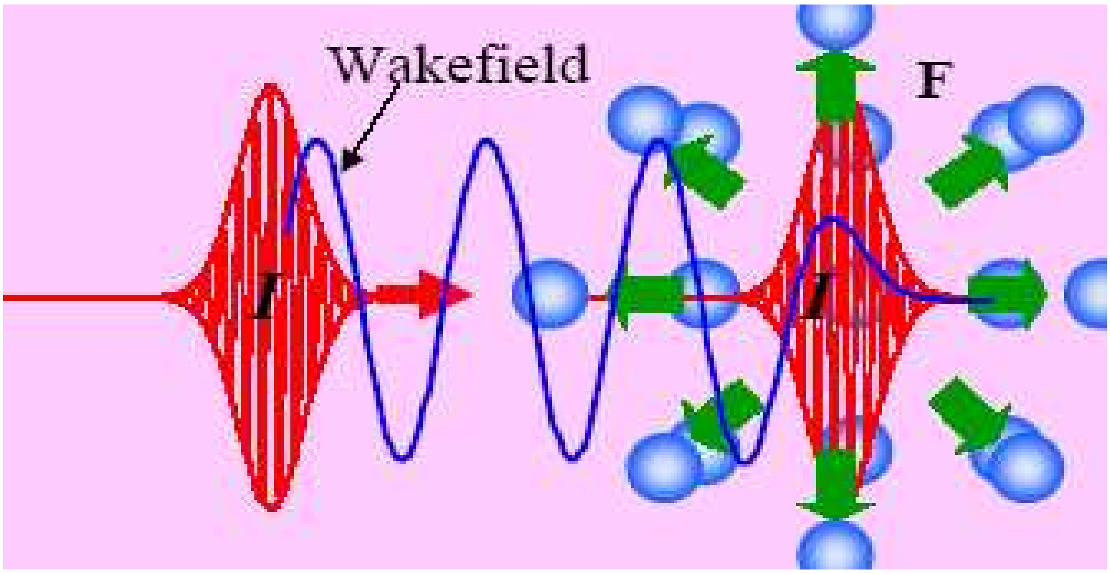

Figure (2-8) The ponderomotive force drives a wakefield in an underdense plasma [39].

In this figure the interaction of an intense laser field (red line) with electrons (blue balls) in an underdense plasma is illustrated. Free electrons are expelled from the strong field region by the ponderomotive force (green arrows) that drives a wakefield in the underdense plasma to accelerate the electrons. The ponderomotive force and wakefield of an electron in a plasma can be calculated from:

$$\vec{F}_p = m_e \, \vec{a}(t) \qquad (2-20)$$

$$\vec{E}_w = \frac{m_e}{e} \, \vec{a}(t) \qquad (2-21)$$

where

$\vec{F}_p$ is the ponderomotive force of an electron in a plasma.

$\vec{E}_w$ is the wakefield of an electron in a plasma.

Chapter Three

Computer Programs

Chapter Three

Computer Programs

3-1 The shape of the laser pulse

The shape of the laser pulse used in the present work is represented by the sinusoidal wave of electric field in the x-direction with a certain value of rising time T_r , fall time T_f and duration time t . One can choose the electric field of the laser pulse as [40]:

for $t \le T_{off}$,

$$\vec{E}(t) = \vec{E}_o \sin(\omega_o t - k r)\left(1 - \exp\left(\frac{-t}{T_r}\right)\right) \qquad (3-1)$$

for $t > T_{off}$,

$$\vec{E}(t) = \vec{E}_o \sin(\omega_o t - k r)\left(1 - \exp\left(\frac{-t}{T_r}\right)\right) \exp\left(-\frac{(t - T_{off})}{T_f}\right) \qquad (3-2)$$

where

ω_o is the angular frequency of laser pulse ,

T_{off} is the time at which driving field is switched off, and

k is the wave number.

A computer program was written in FORTRAN 90 language called "Laser Shape" using the software environment Fortran

Power Station V_4 [41] to generate the shape of the laser pulse that interacts with the electron and plasma. Appendix (C) shows the flowchart for the "Laser Shape" program.

3-2 Calculation of the acceleration, velocity, position and energy for an electron in vacuum

The acceleration of an electron in vacuum is due to the interaction of the laser pulse (can be simulated by using "Laser Shape" program) with the electron. The acceleration of an electron in the x-direction can be calculated from [25, 32]:

$$a_x(t) = \frac{e}{m_e} E_x(t) \qquad (3-3)$$

From the equation of motion, the velocity of the electron in the x-direction is given by [42]:

$$v_x(t) = v_{x_o}(t) + a_x(t)\,\Delta t \qquad (3-4)$$

where $v_{xo}(t)$ is the initial velocity of the electron.

In the present work, $v_{xo}(t)$ of the electron is assumed to be zero and Δt is the increment in time. The position of the electron in the x-direction can be calculated from:

$$x(t) = v_{x_o}(t)\,\Delta t + \frac{1}{2} a_x(t)\,\Delta t^2 \qquad (3-5)$$

where x(t) is the position of the electron after the interaction.

The kinetic energy of the electron during and after the interaction in the x-direction can be calculated from:

$$E_{kx} = \frac{1}{2} m_e \, v_x^2 \qquad (3-6)$$

Repeating the calculations of acceleration, velocity, position and energy for the electron for N times of (Δt) one can calculate the acceleration, velocity, position and energy of the electron throughout the duration of the laser pulse.

Using eqs.(3-3), (3-4), (3-5) and (3-6), a computer program was written in FORTRAN 90 language called " Electron-Laser" to calculate the acceleration, velocity, position and energy of the electron during and after the interaction. Appendix (D) shows the flowchart of this "Electron-Laser" program.

3-3 Calculation of the acceleration, velocity, position, energy and wakefield during and after the interaction of laser pulse with a plasma

The acceleration of an electron in a plasma is due to the interaction of the laser pulse with the plasma based on the Finite Difference Method and can be calculated from [34]:

$$a_x(t) = \frac{e}{m_e} E_x(t) - \omega_p^2 \, \delta_x \qquad (3-7)$$

where δ_x is the displacement of the electron in the x-direction. From the equation of motion, the velocity, position and kinetic energy of the electron in the x-direction can be calculated from eqs.(3-4), (3-5) and (3-6).

Repeating the acceleration, velocity, position and energy calculations for the electron for N times of (Δt) one can calculate the acceleration, velocity, position and energy throughout the duration of the laser pulse.

Using eqs.(3-4), (3-5), (3-6) and (3-7), a computer program was written in FORTRAN 90 language called " Laser- Plasma" to calculate the acceleration, velocity, position and energy of the electron during and after the interaction. In addition, the program calculates the ponderomotive force F_{p_x} and wakefield $E_{w\,x}$ in the x-direction by substituting eq. (3-7) in eq. (2-20) and eq. (2-21) to obtain:

$$F_{p_x} = -m_e\, \omega_p^2\, \delta_x + e\, E_o \sin(\omega_o\, t - k\, x)\left(1 - \exp\left(\frac{-t}{T_r}\right)\right) F_{off} \quad (3-8)$$

$$E_{w\,x} = -\frac{m_e}{e}\, \omega_p^2\, \delta_x + E_o \sin(\omega_o\, t - k\, x)\left(1 - \exp\left(\frac{-t}{T_r}\right)\right) F_{off} \quad (3-9)$$

where,

$$F_{off} = \begin{cases} 1 & \text{for} \quad t \le T_{off} \\ e\exp\left(-\left(\dfrac{t - T_{off}}{T_r}\right)\right) & \text{for} \quad t > T_{off} \end{cases}$$

The input data for the "Laser-Plasma" program are the charge, mass, initial velocity and initial position in x-direction, of the electron and plasma density.

The output data from this program are the acceleration, velocity, position and energy of the electron in x-direction. In addition, the ponderomotive force and wakefield caused by the laser pulse are also calculated in this program. Appendix (E) shows the flowchart for the "Laser-Plasma" program.

3-4 Calculation of the acceleration, velocity, displacement, energy and wakefield during and after the interaction of laser pulse with a magnetized plasma

The displacement of the electron from its initial position in the x- and y-directions can be calculated from [34]:

$$\rho_x(t) = x(t)\left(1 - \frac{R_L}{|r|}\right) \qquad (3-10)$$

$$\rho_y(t) = y(t)\left(1 - \frac{R_L}{|r|}\right) \qquad (3-11)$$

The acceleration of an electron in the x- and y- directions can be calculated from the equations [34]:

$$a_x(t) = \frac{e}{m_e} E_x(t) + \omega_c \, v_y(t) - \omega_p^2 \, \rho_x(t) \qquad (3-12)$$

$$a_y(t) = -\omega_c \, v_x(t) - \omega_p^2 \, \rho_y(t) \qquad (3-13)$$

The velocity, position and kinetic energy of the electron in the x-direction can be calculated from eqs.(3-4), (3-5) and (3-6). The velocity, position and kinetic energy of the electron in the y-direction can be calculated from [42]:

$$v_y(t) = v_{y_o} + a_y(t)\,\Delta t \qquad (3-14)$$

$$y(t) = v_{y_o}\,\Delta t + \frac{1}{2} a_y(t)\,\Delta t^2 \qquad (3-15)$$

$$E_{k\,y} = \frac{1}{2} m_e \, v_y^2 \qquad (3-16)$$

The ponderomotive force and wakefield caused by the laser pulse in the x- and y- directions can be calculated from substitution of eqs. (3-12) and (3-13) into eqs. (2-20) and (2-21), to obtain:

$$F_{p_x} = -m_e\, \omega_p^2\, \rho_x(t) + e\, E_o \sin(\omega_o\, t - k\, x)\left(1 - \exp\left(\frac{-t}{T_r}\right)\right) F_{off}$$
$$+ m_e\, \omega_c\, v_y(t) \qquad (3-17)$$

$$F_{p_y} = -m_e\, \omega_p^2\, \rho_y(t) - m_e\, \omega_c\, v_x(t) \qquad (3-18)$$

$$E_{w_x} = -\frac{m_e}{e}\, \omega_p^2\, \rho_x(t) + E_o \sin(\omega_o\, t - k\, x)\left(1 - \exp\left(\frac{-t}{T_r}\right)\right) F_{off}$$
$$+ \frac{m_e}{e}\, \omega_c\, v_y(t) \qquad (3-19)$$

$$E_{w_y} = -\frac{m_e}{e}\, \omega_p^2\, \rho_y(t) - \frac{m_e}{e}\, \omega_c\, v_x(t) \qquad (3-20)$$

Repeating the acceleration, velocity, position and energy calculations for the electron for N times of Δt one can calculate these quantities throughout the duration of the laser pulse.

A computer program called " Laser-Magnetized Plasma" was written in FORTRAN 90 language using eqs.(3-10), (3-11), (3-12), (3-13), (3-14), (3-15), (3-16), (3-17), (3-18), (3-19) and (3-20) to calculate the acceleration, velocity, position ,displacement and kinetic energy of the electron, in addition to the ponderomotive force and the wakefield caused by the laser pulse during and after the interaction. Appendix (F) shows the flowchart for the "Laser-Magnetized Plasma" program.

Chapter Four

Results and Discussion

Chapter Four

Results and Discussion

4-1 Shape of the laser pulse

The shape of a Nd: YAG laser pulse is determined using the "Laser Shape" program. The intensity of the laser pulse shown in table (4-1) was chosen according to the non-relativistic interactions that occur at $a_o < 1$ [5], and the time of the laser pulse can be calculated from the length of the laser pulse.

Table (4-1) The input data for the "Laser Shape" program

I	$5x10^{15}$(W/cm^2)
t	$25x10^{-15}$(sec)
T_r	$0.3x10^{-14}$(sec)
T_f	$0.3x10^{-14}$(sec)
T_{off}	$1.7x10^{-14}$(sec)
m_e	$9.1x10^{-28}$(gm)
x	0
λ_o	$1.06x10^{-4}$ (cm)
e	$4.8x10^{-10}$(esu)

The output data from the "Laser Shape" program are illustrated in Fig.(4-1).

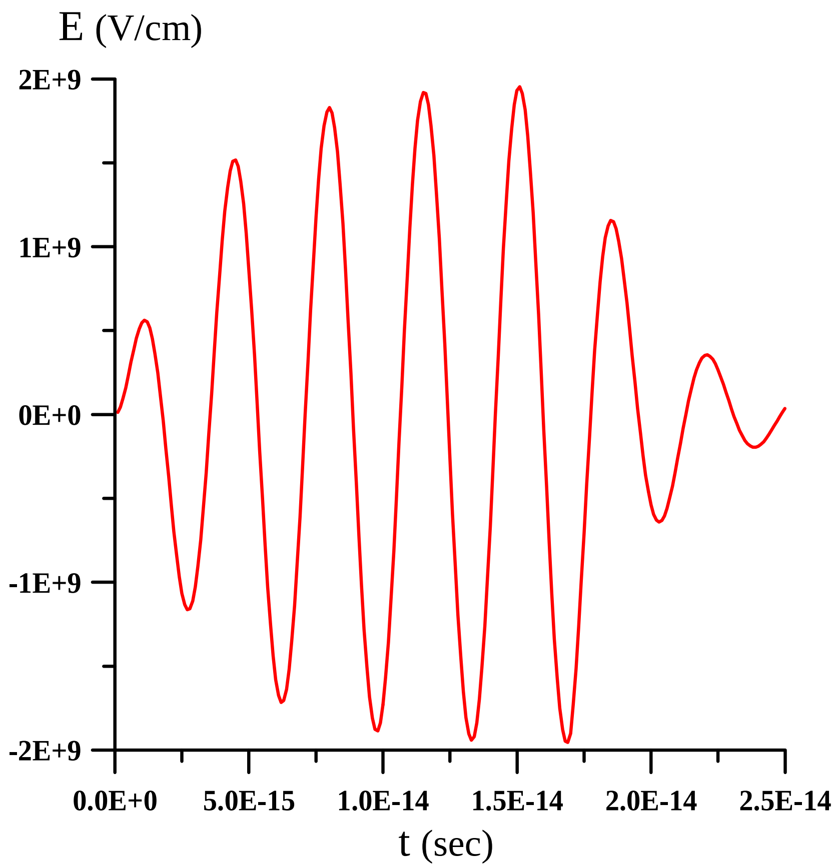

Figure (4-1) Electric field for a Nd:YAG laser pulse as a function of pulse time for $I=5x10^{15}(W/cm^2)$.

From Fig.(4-1), it can be seen that the value of maximum electric field amplitude E_o~ $2x10^9$ V/cm is obtained for the value of the intensity of the laser pulse I $=5x10^{15}$ W/cm^2 that is directly proportional to the unitless laser amplitude a_o ~ $7x10^{-2}$, as calculated from eq.(2-3). The electric field for a Nd:YAG laser pulse was calculated using eqs. (3-1) and (3-2).

4-2 Calculation of the acceleration for a single electron in vacuum

The acceleration for a stationary single electron in vacuum is determined using the "Electron-Laser" program with input data shown in table (4-2).

Table (4-2) The input data for the (Electron-Laser) program

I	$5\text{x}10^{15}$(W/cm^2)
t	$25\text{x}10^{-15}$(sec)
T_r	$0.3\text{x}10^{-14}$(sec)
T_f	$0.3\text{x}10^{-14}$(sec)
T_{off}	$1.7\text{x}10^{-14}$(sec)
m_e	$9.1\text{x}10^{-28}$(gm)
x_o	0
v_{xo}	0
λ_o	$1.06\text{x}\ 10^{-4}$ (cm)
e	$4.8\text{x}10^{-10}$(esu)

From this program and using these parameters, one can study the behavior and maximum values of the velocity, position and energy for the electron resulting from the laser pulse propagation.

4-2-1 Calculation of the velocity for an electron in vacuum

The velocity for an electron is determined with input parameters as shown in table (4-2) using the "Electron-Laser" program.

The results for this case corresponding to the laser intensity $I = 5x10^{15}$ W/cm^2 are illustrated in Fig.(4-2).

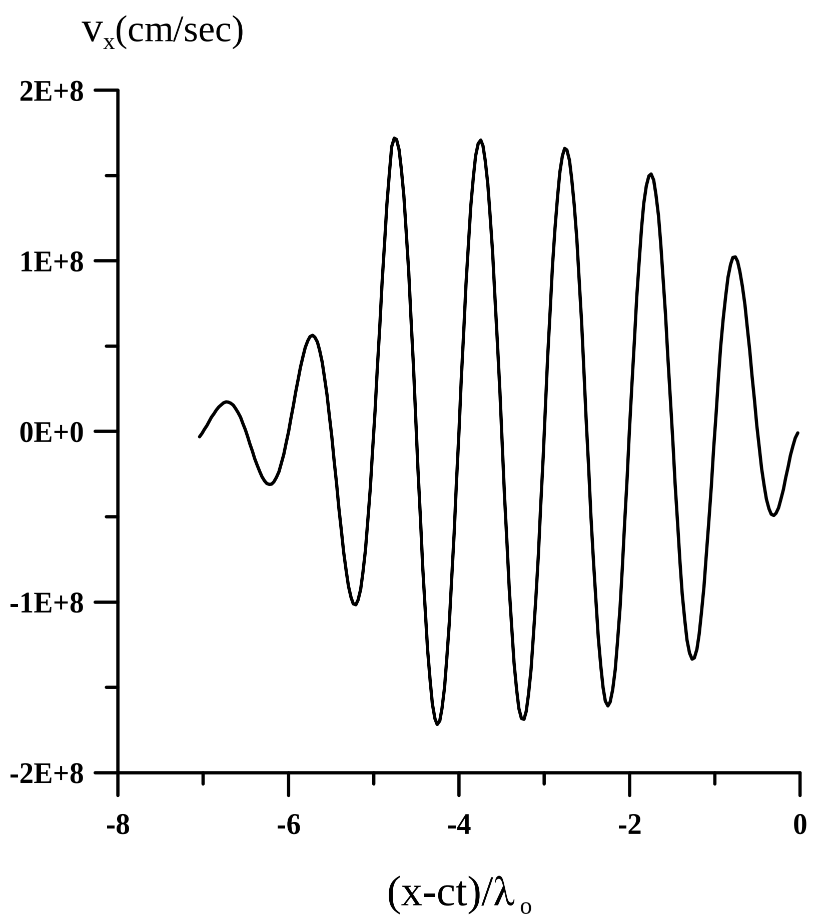

Figure (4-2) The velocity of the electron as a function of distance normalized by λ_o for $I = 5x10^{15}$(W/cm^2).

It is noticed from Fig.(4-2) that the maximum value of the velocity of the electron during the interaction as a result of the laser pulse propagation reached to $v_x \sim 2x10^8$ cm/sec .

It was found that when the laser intensity is multiplied by a factor of a 100 the maximum velocity of the electron in the x-direction during the interaction increased by a factor of about 10. This is due to the increase in the electric field that results from the interaction. From the calculation of the velocity of an electron using the "Electron-Laser" program, one can see the oscillation of the electron during and after the propagation of the laser pulse as shown in Figs.(4-3)and (4-4).

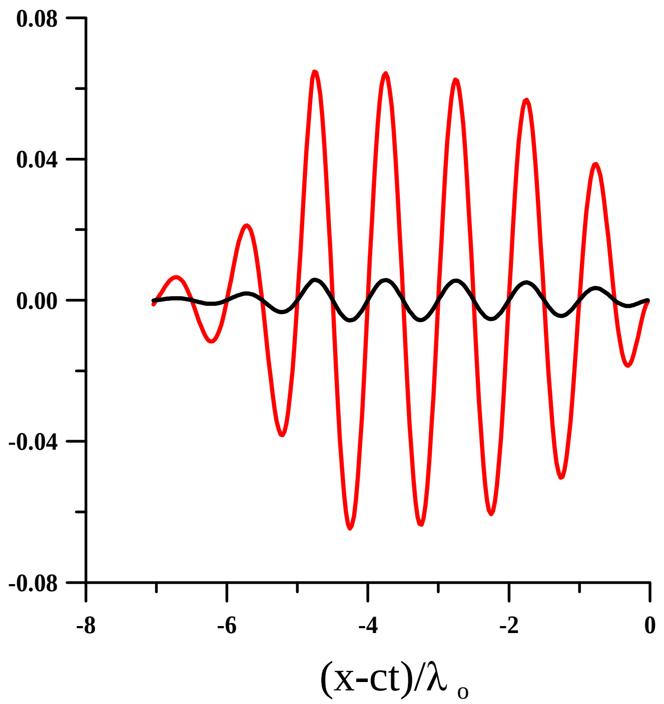

Figure (4-3) The laser pulse unitless amplitude (red line) and electron momentum (black line),where the x-axis is normalized by λ_o and the y-axis is the unitless amplitude a for the laser pulse and β for the momentum of the electron at $I=5x10^{15}(W/cm^2)$.

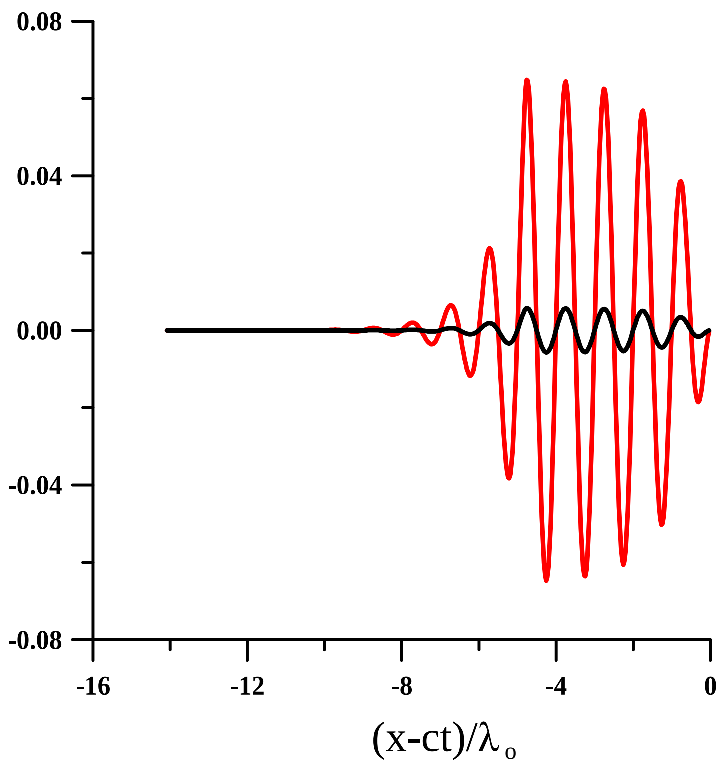

Figure (4-4) Acceleration of the electron after the interaction with a laser pulse, where the x-axis is normalized by λ_o and the y-axis is the unitless amplitude a for the laser pulse and β for the momentum of the electron at $I=5x10^{15}(W/cm^2)$.

One can define β as the Lorentz factor and equal to (v/c).During the interaction, when the laser pulse propagation, the electron oscillations during the laser pulse and has momentum, as shown in Fig.(4-3).

After the interaction, when the laser pulse has passed, the electron returns to its stationary state. This means, that the electron has no momentum after the interaction because no net acceleration occurs to the electron or the net force on the electron is zero, as shown in Fig.(4-4).

In a previous work, S. Eliezer and K. Mima in 2009 [25] used a laser pulse with duration time (Δt=30 fs), wavelength (λ_o=1μm) and maximum intensity (I= $3x10^{17}$ W/cm^2). This laser pulse interacted with an electron at rest by using the numerical integration of the equations of motion. They noticed that the electron is accelerated during the interaction but after the laser pulse has passed the electron has no acceleration as shown in Fig.(4-5). The result of the present work illustrated in Fig.(4-3) has the same behavior as the result of Eliezer and Mima shown in Fig.(4-5).

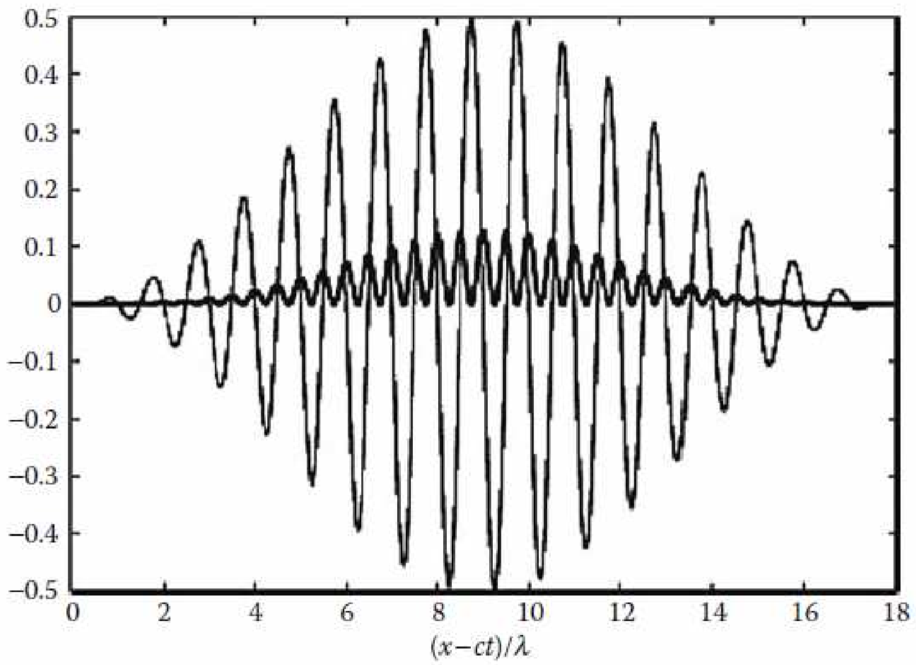

Figure (4-5) Laser pulse (light line) and electron momentum (dark thick line) where the x-axis is normalized by λ_o and the y-axis is the unitless amplitude a for the laser pulse and $\gamma\beta_x$ for the momentum of electron [25].

where $\gamma\beta_x$ is the Lorentz factors.

4-2- 2 Calculation of the kinetic energy of an electron in vacuum

The kinetic energy of an electron in vacuum can be determined using the "Electron-Laser" program.

The results of the calculations are illustrated in Fig.(4-6).

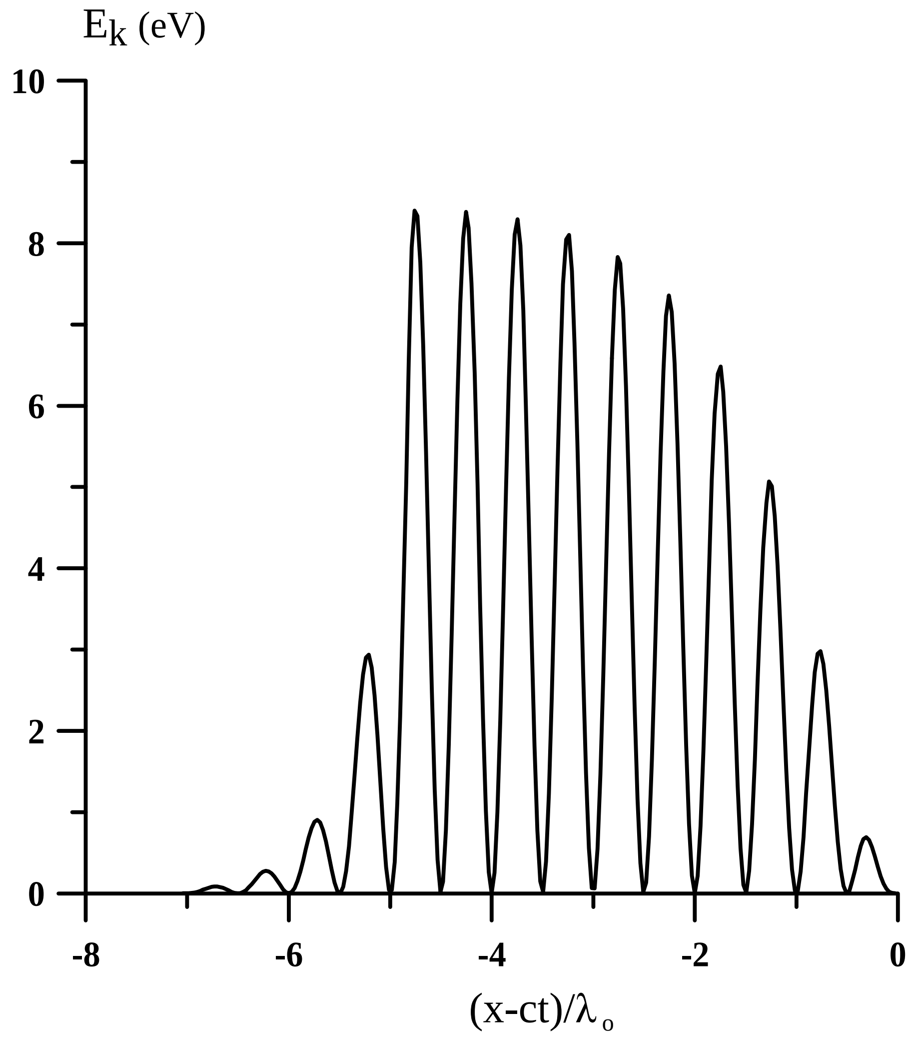

Figure (4-6) The kinetic energy of an electron as a function of distance normalized by λ_o for $I=5x10^{15}(W/cm^2)$.

From this figure, it is noticed that the electron is accelerated during the interaction with the laser pulse for I = $5x10^{15}$ W/cm^2 to a maximum value of the kinetic energy of an electron E_k ~ 8 eV .

After the laser pulse has passed the electron is again stationary with no net energy.

4-3 Calculation of the acceleration of an electron in a plasma

The acceleration of an electron in a homogenous collisionless plasma by a laser pulse is calculated using the program "Laser-Plasma" with the input data shown in table (4-3).

The critical density of the plasma is determined using eq.(2-7), to be $1x10^{21}cm^{-3}$. But, in the present work, the plasma is assumed to be underdense, therefore, one can choose the value of the plasma density $n_e=1x10^{18}cm^{-3}$.

Table (4-3) The input data for the "Laser- Plasma" program

I	$5x10^{15}$(W/cm^2)
t	$25x10^{-15}$ (sec)
T_r	$0.3x10^{-14}$ (sec)
T_f	$0.3x10^{-14}$ (sec)
T_{off}	$1.7x10^{-14}$ (sec)
n_e	$1x10^{18}$ (cm^{-3})
x_o	0
v_{xo}	0

4-3-1 Calculation of the velocity for an electron in a plasma

When a laser pulse, as illustrated in Fig.(4-1), interacts with a plasma, whose density $n_e=1x10^{18}cm^{-3}$ and frequency $\omega_p=5.4x10^{13}$ rad/sec , the electron is accelerated from initial velocity (v_{xo}= 0) at initial position (x_o= 0) according to the Lorentz force plus the force that results from the oscillation of the electron in the plasma calculated using the "Laser-Plasma" program.

The results for this case with the intensity of the laser pulse I= $5x10^{15}$ W/cm^2 are illustrated in Fig.(4-7).

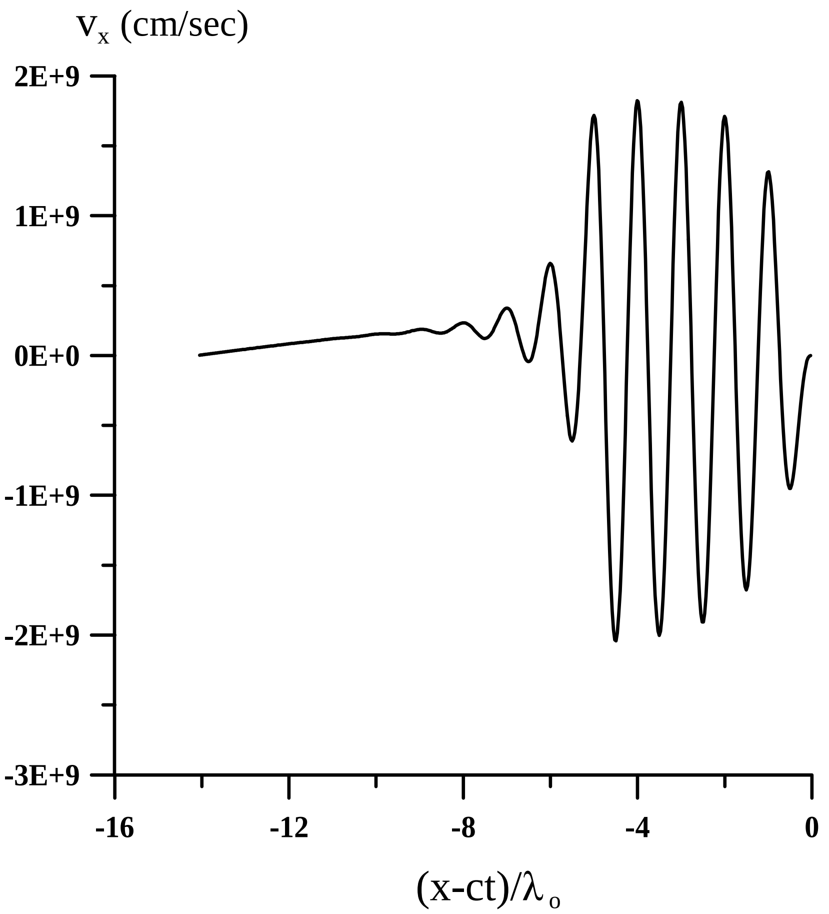

Figure (4-7) The velocity of the electron resulting from the laser pulse propagation, and after the laser pulse has passed, for $I=5x10^{15}$(W/cm^2).

Fig.(4-7) illustrates the velocity of the electron in the x-direction in a plasma during and after the interaction that results from the electric force in addition to the oscillation force of the electron in the plasma. The maximum velocity of the electron in the x-direction during the interaction reached to $v_x \sim 2x10^9$ cm/sec, while the maximum velocity of the electron in the x-direction after the interaction reached to $v_x \sim 2x10^8$ cm/sec. It is noticed that the velocity of the electron during the interaction is larger than the velocity of the electron after the interaction. This is due to the decline in the electric field after the laser pulse has passed.

Results of calculation of the velocity of the electron using the "Laser-Plasma" program illustrate the oscillation of the electron in a plasma during and after the propagation of the laser pulse as shown in Figs.(4-8) and (4-9).

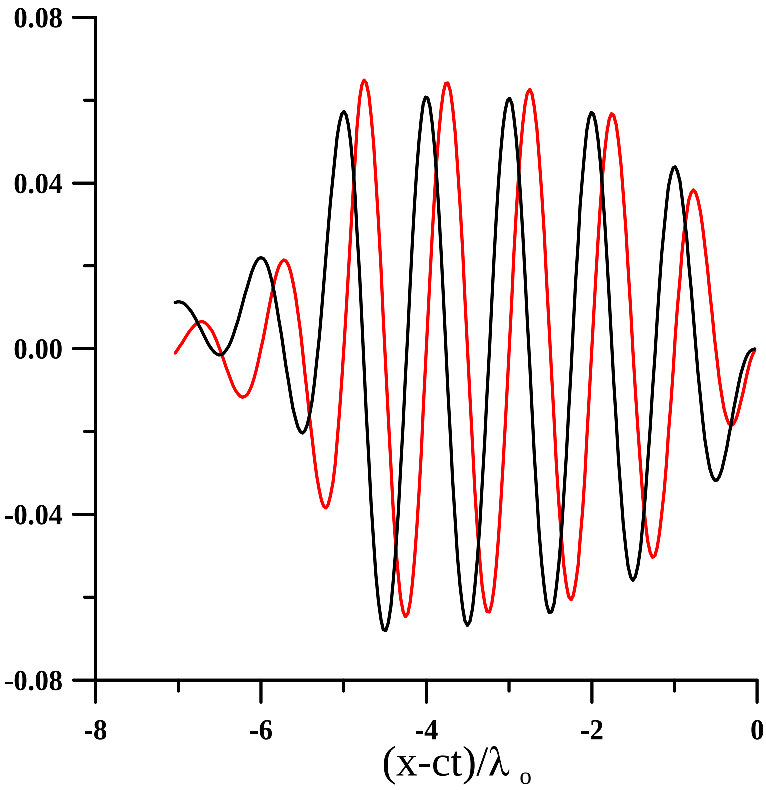

Figure (4-8) The unitless amplitude of the laser pulse (red line) and electron momentum (black line) where the x-axis is normalized by λ_o and the y-axis is the unitless amplitude a for the laser pulse and β for the momentum of the electron at $I=5x10^{15}(W/cm^2)$.

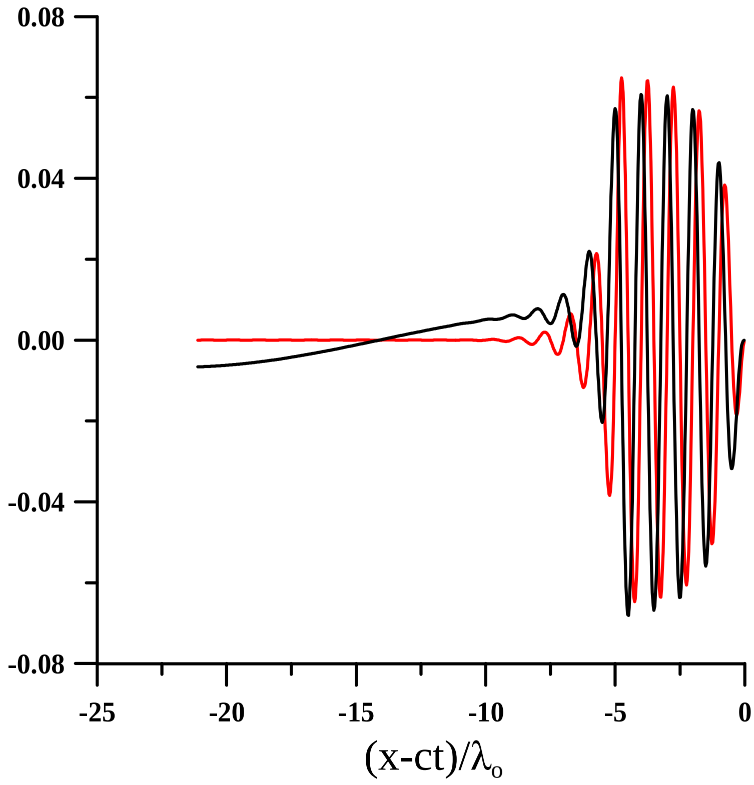

Figure (4-9) Acceleration of the electron in a plasma by a laser pulse where the x-axis is normalized by λ_o and the y-axis is the unitless amplitude a for the laser pulse(red line)and β for the momentum of the electron(black line) for I=5x10^{15}(W/cm^2).

In a previous work, S. Eliezer and K. Mima in 2009 [25] used a laser pulse with duration time (Δt=16.7 fs), wavelength (λ_o= 1μm) and maximum intensity of (I=3x10^{17} W/cm^2).This laser pulse interacted with a plasma of density (n_e= 5x10^{18} cm^{-3}) using (PIC) technique. They noted that the electrons in the plasma were accelerated during and after the interaction as shown in Figs.(4-10) and (4-11). The results of the present work based on the Finite Difference Method are illustrated in Figs.(4-8) and

(4-9). It is noticed that these results have the same behavior as the results of Eliezer and Mima [25] shown in Figs.(4-10) and (4-11).

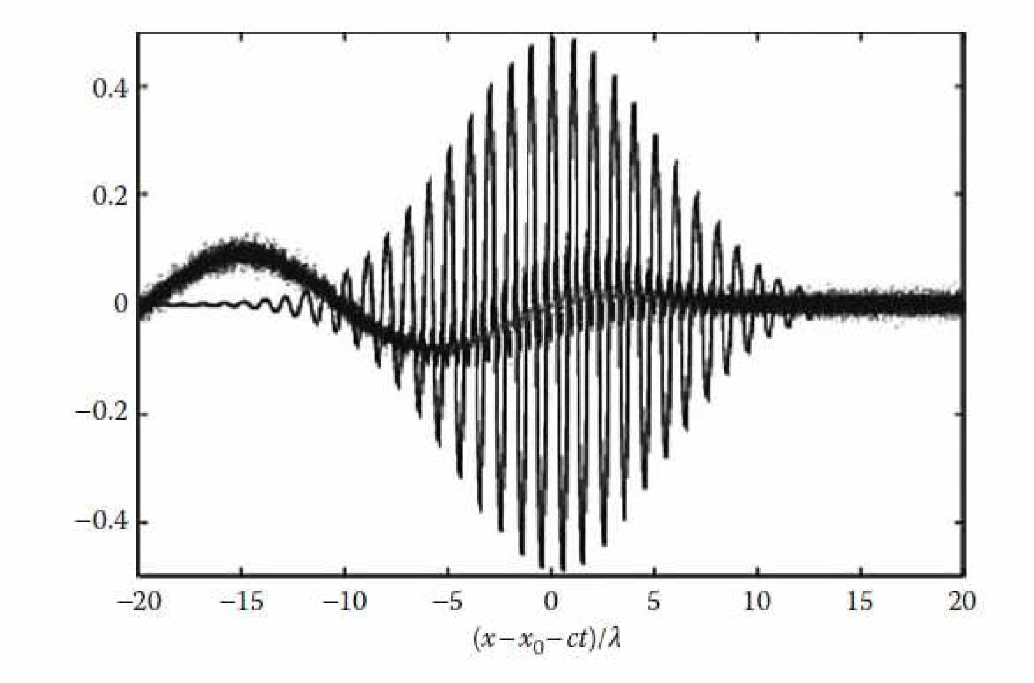

Fig.(4-10) Pushing of plasma electrons by a laser pulse[25].

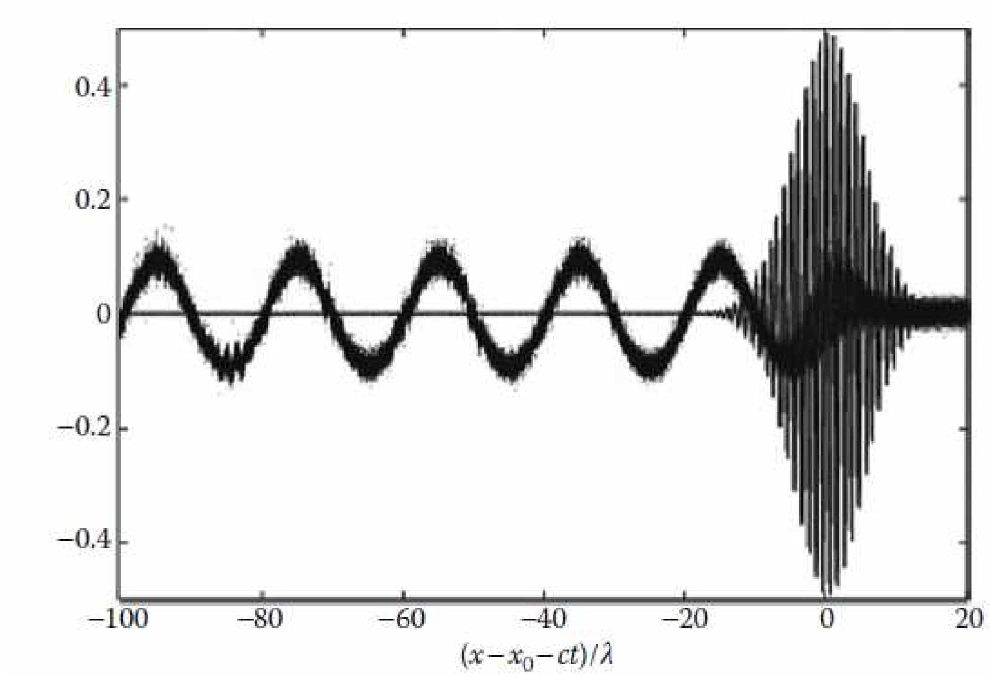

Fig.(4-11) Expanded view of plasma electrons behind the laser pulse[25].

4-3-2 Calculation of the kinetic energy for an electron in a plasma

When a laser pulse interacts with a plasma, the electron has kinetic energy in the x-direction during and after the laser pulse propagation resulting from the velocity of the electron in the plasma.

The kinetic energy for an electron in a plasma can be calculated using the "Laser-Plasma" program.

The results of these calculations are illustrated in Fig.(4-12).

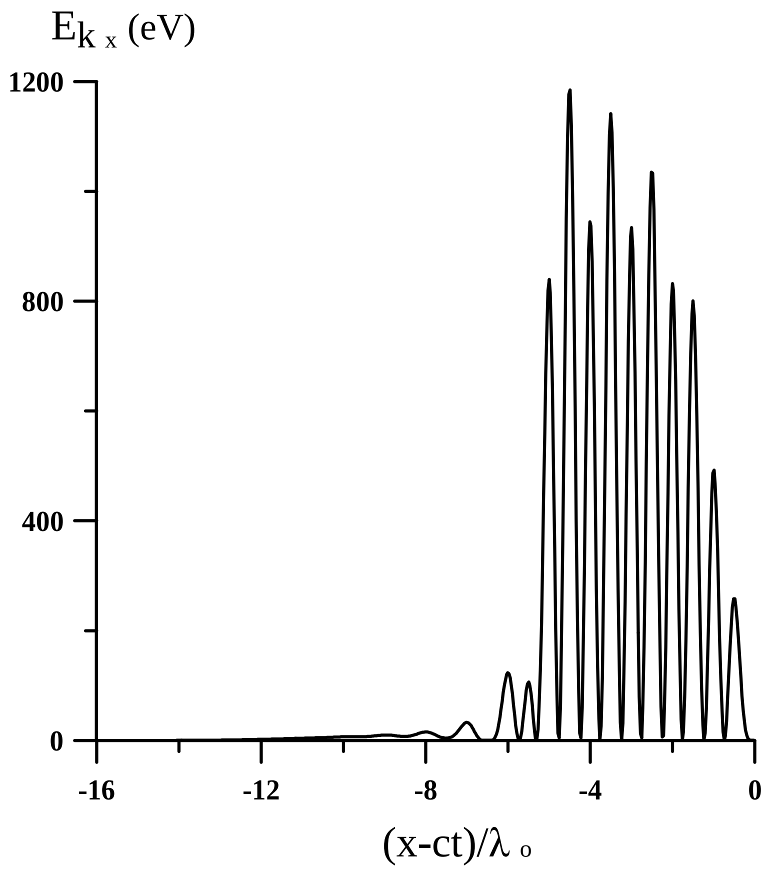

Figure (4-12) The kinetic energy of the electron resulting from the laser pulse propagation and after the laser pulse has passed for $I=5x10^{15}(W/cm^2)$.

From this figure one can determine the maximum value of the kinetic energy of the electron in the x-direction during the interaction to be $E_{k_x} \sim 1$ keV, while, after the laser pulse has passed the maximum value of the kinetic energy of the electron in the x-direction is $E_{k_x} \sim 15$ eV. The decrease in the kinetic energy of the electron behind the laser pulse is due to the decline of the wakefield after the laser pulse has passed.

4-4 Calculation of the acceleration of an electron in a magnetized plasma

The acceleration of an electron in a magnetized plasma is determined using the "Laser-Magnetized Plasma" program with the parameters shown in table (4-4). The values of magnetic field applied on the plasma have been chosen so that the electron is always in the non-relativistic region.

Table (4-4) The input data for the "Laser-Magnetized Plasma" program

I	$5x10^{15}$(W/cm^2)
t	$25x10^{-15}$(sec)
T_r	$0.3x10^{-14}$(sec)
T_f	$0.3x10^{-14}$(sec)
T_{off}	$1.7x10^{-14}$(sec)
m_e	$9.1x10^{-28}$(gm)
λ_o	$1.06\ x10^{-4}$(cm)
e	$4.8x10^{-10}$(esu)
n_e	$1x10^{18}$(cm^{-3})
v_{xo}	0
v_{yo}	0
x_o	0
y_o	0
B	60 (MG) ,70 (MG), 80 (MG)

4-4-1 Calculation of the velocity of an electron in a magnetized plasma

In this case, the electron is accelerated according to the Lorenz equation that includes electric and magnetic forces in addition to the oscillation force of the electron in the plasma.
The velocity of the electron attained as a result of the acceleration in the plasma during and after the interaction, is illustrated in Fig.(4-13) for an intensity of the laser pulse I= $5x10^{15}$ W/cm^2 and various values of the external magnetic field applied on the plasma.

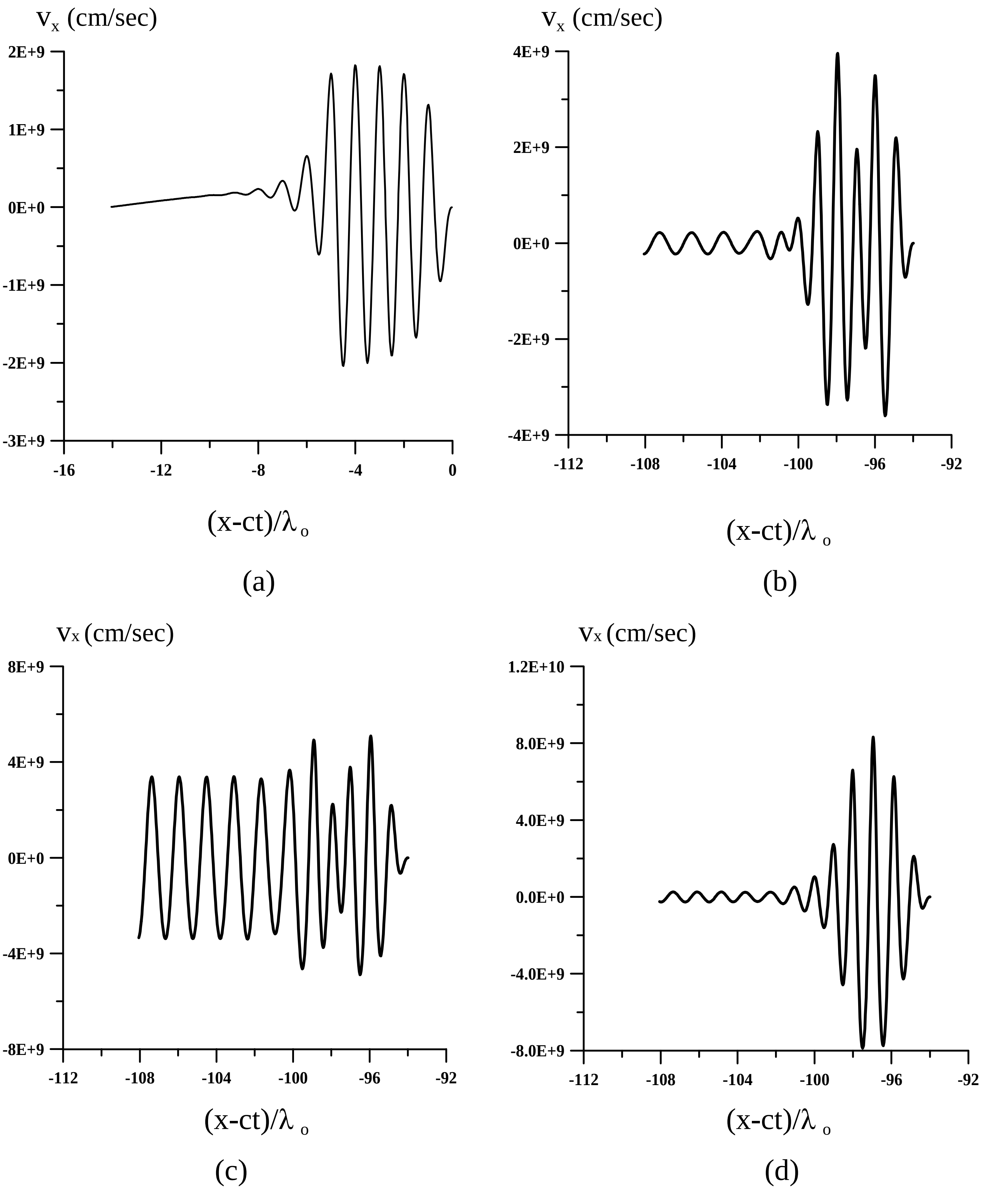

Figure (4-13) The velocity of electron in the x-direction in a magnetized plasma, during and after the interaction, for intensity of laser pulse $I=5x10^{15}$ (W/cm^2) and (a) B=0 (b) B=60MG, (c) B=70MG, (d) B=80MG.

One can notice from Fig. (4-13) that the velocity of the electron in the x-direction in a magnetized plasma increases when the value of external applied magnetic field increases. This is due to the increase in the displacement of the electron from its initial position and form the cyclotron frequency for the electron which leads to the increase of its acceleration, velocity and energy.

The maximum values of the velocity of the electron in the x-direction are illustrated in table (4-5).

Table (4-5) The maximum values of the velocity of the electron for $I=5x10^{15}(W/cm^2)$.

B(MG)	v_x (cm/sec) (during interaction)	v_x (cm/sec) (after interaction)
0	2.0×10^9	2.3×10^8
60	3.9×10^9	3.2×10^8
70	5.0×10^9	34×10^8
80	8.3×10^9	2.6×10^8

From table (4-5), one can see the maximum velocity of the electron in the x-direction during the interaction is about 4 times the velocity of the electron in a non-magnetized plasma. But , after the laser pulse has passed, the maximum velocity of the electron in the x-direction increases to about 15 times compared with its value in the non-magnetized plasma when B=70 MG.

The calculations for the velocity of the electron in the y-direction indicated that it is nearly the same as its velocity in the x-direction and have the same behavior. For this reason, there is no need to draw the behavior of the velocity in the y-direction.

For the three values of the external magnetic field applied on the plasma and for an intensity of the laser pulse I= $5x10^{15}$ W/cm^2, one can describe the propagation of the laser pulse and the acceleration of the electron in a magnetized plasma. More details of this behavior are shown in Fig.(4-14).

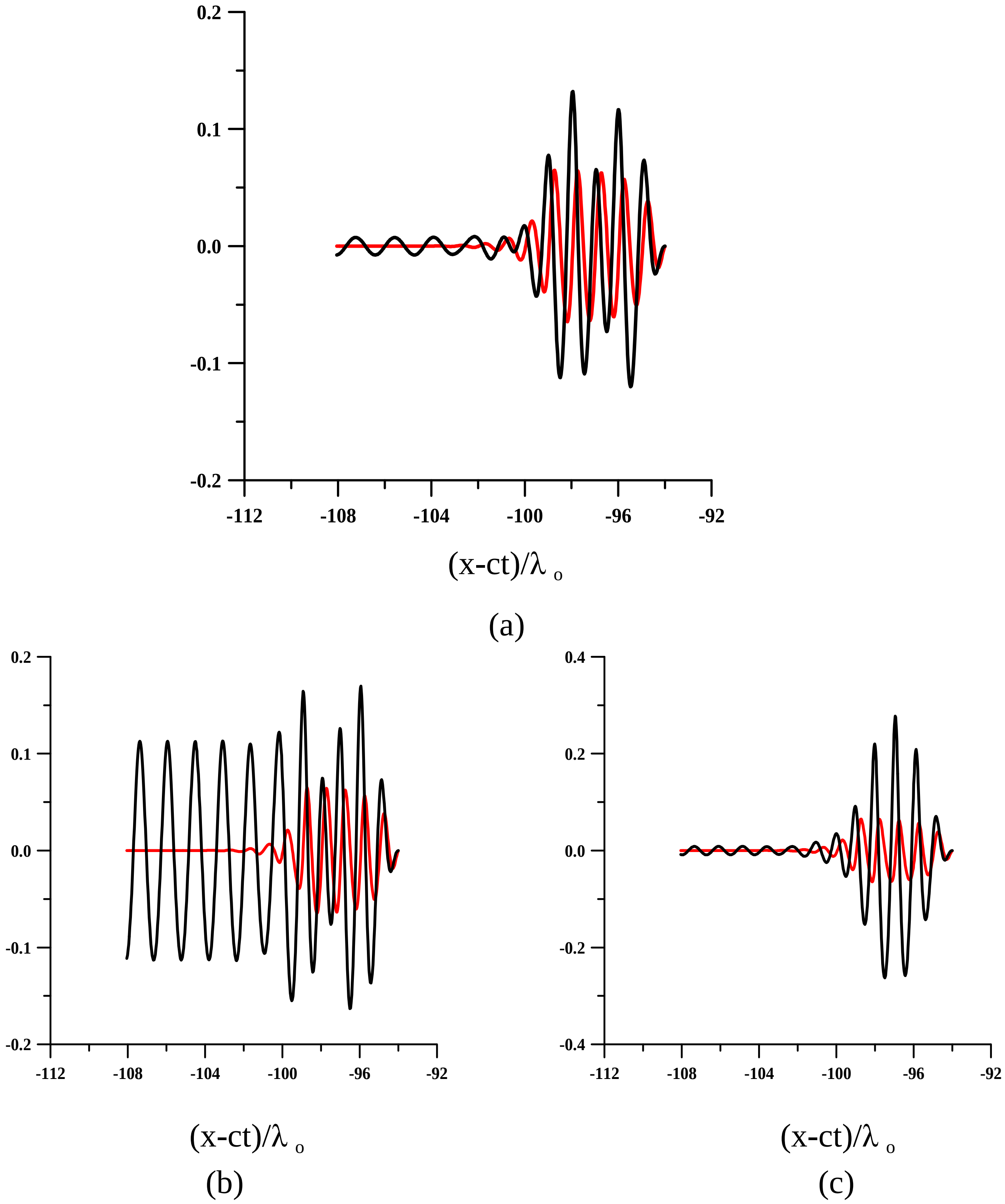

Figure (4-14) The laser pulse (red line), the momentum (black line), where the x-axis is normalized by λ_o and the y-axis is the unitless amplitude a for the laser pulse of intensity $I=5x10^{15}$ (W/cm^2)and β for the momentum of the electron for (a) B=60 MG,(b) B=70 MG, and (c) B =80 MG.

4-4-2 Calculation of the kinetic energy of an electron in a magnetized plasma

The effect of an external magnetic field on the kinetic energy for an electron is studied with the different three values of magnetic field. The results are illustrated in Fig.(4-15).

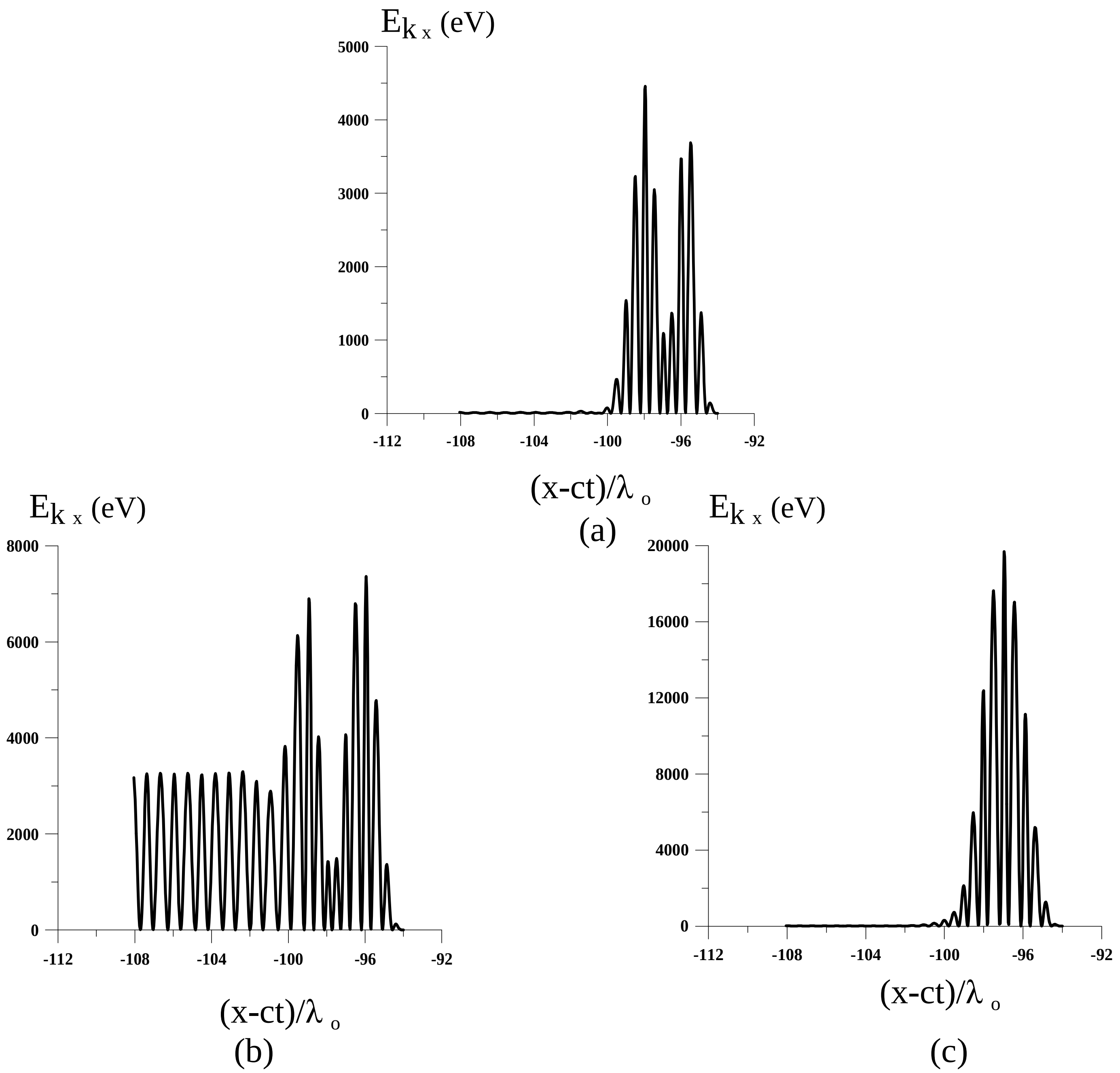

Figure (4-15) The kinetic energy of an electron in a magnetized plasma during and after the interaction for intensity of laser pulse $I=5\text{x}10^{15}$(W/cm^2) and (a) B=60 MG, (b) B=70 MG,(c) B=80 MG.

The maximum values of the kinetic energy for an electron are shown in table (4-6).

Table (4-6) The maximum values for the kinetic energy of an electron during and after the interaction for I=5x10^{15}(W/cm^2).

B(MG)	E_k (eV) (during interaction)	E_k (eV) (after interaction)
0	1185	15.1
60	4458	30.6
70	7365	3261
80	1.9 x10^4	20.2

From this table, one can notice that the maximum kinetic energy of the electron during the interaction can increase to about 20 times for B=80MG and 200 times for B=70 MG compared with its value after the interaction in a non-magnetized plasma.

4-5 Calculation of the laser wakefield in a plasma

When a laser pulse propagates in a plasma, it sets the electrons into transverse oscillation (electron trapping) with a net gain of energy in the region behind the pulse [38].

Using the "Laser-Plasma" program, the laser wakefield, which is generated during and after the interaction, can be calculated. The results of these calculations are illustrated in Figs.(4-16) and (4-17).

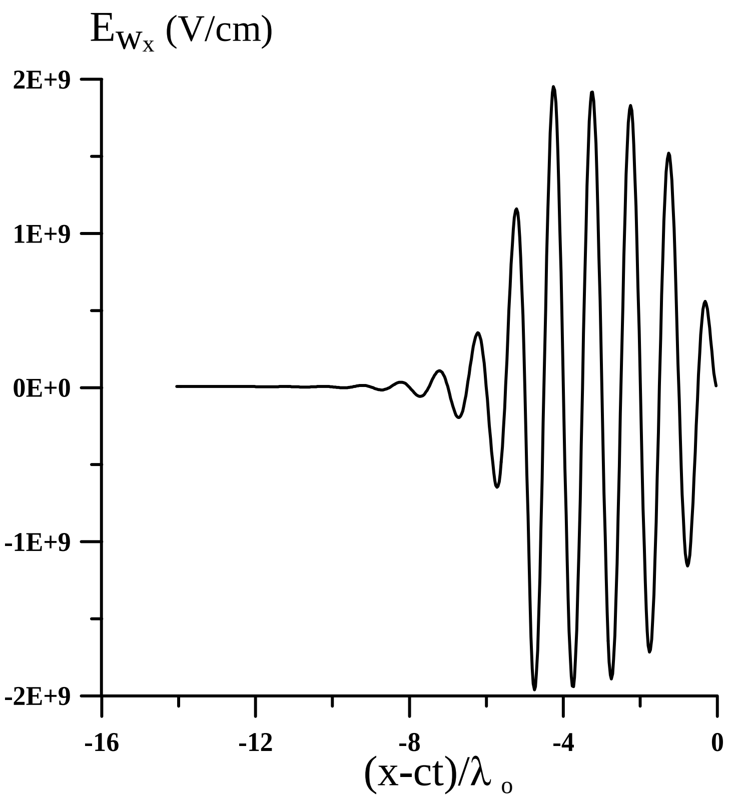

Figure (4-16) The wakefield of a laser pulse during and after the interaction as a function of distance normalized by λ_o for $I=5x10^{15}(W/cm^2)$.

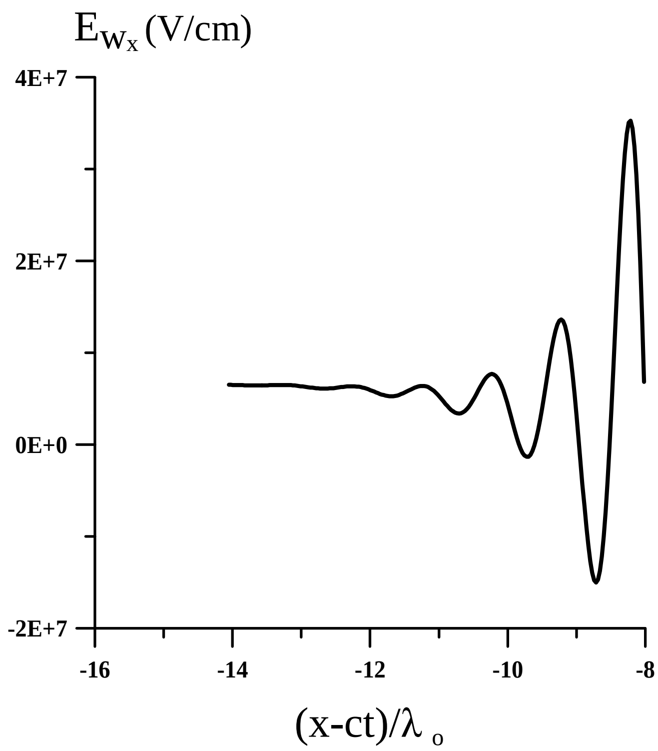

Figure (4-17) The wakefield of a laser pulse after the interaction as a function of distance normalized by λ_o for $I=5x10^{15}(W/cm^2)$.

From theses figures, it can be noticed that the maximum calculated value of the laser wakefield during the interaction is $E_W \sim 2\ x10^{9}$ V/cm, while, after the laser pulse has passed

$E_W \sim 3.5x10^{7}$ V/cm.

In the same manner, when a laser pulse interacts with a magnetized plasma, the electrons oscillate with an amplitude larger than that for a non-magnetized plasma because the acceleration of the electron is larger, that formed from the large displacement of the electron from its initial position due to the applied of an external magnetic field on a plasma.

Using the "Laser-Magnetized Plasma" program, one can calculate the laser wakefield of the interaction. Fig.(4-18) shows the behavior of the laser wakefield during and after the interaction.

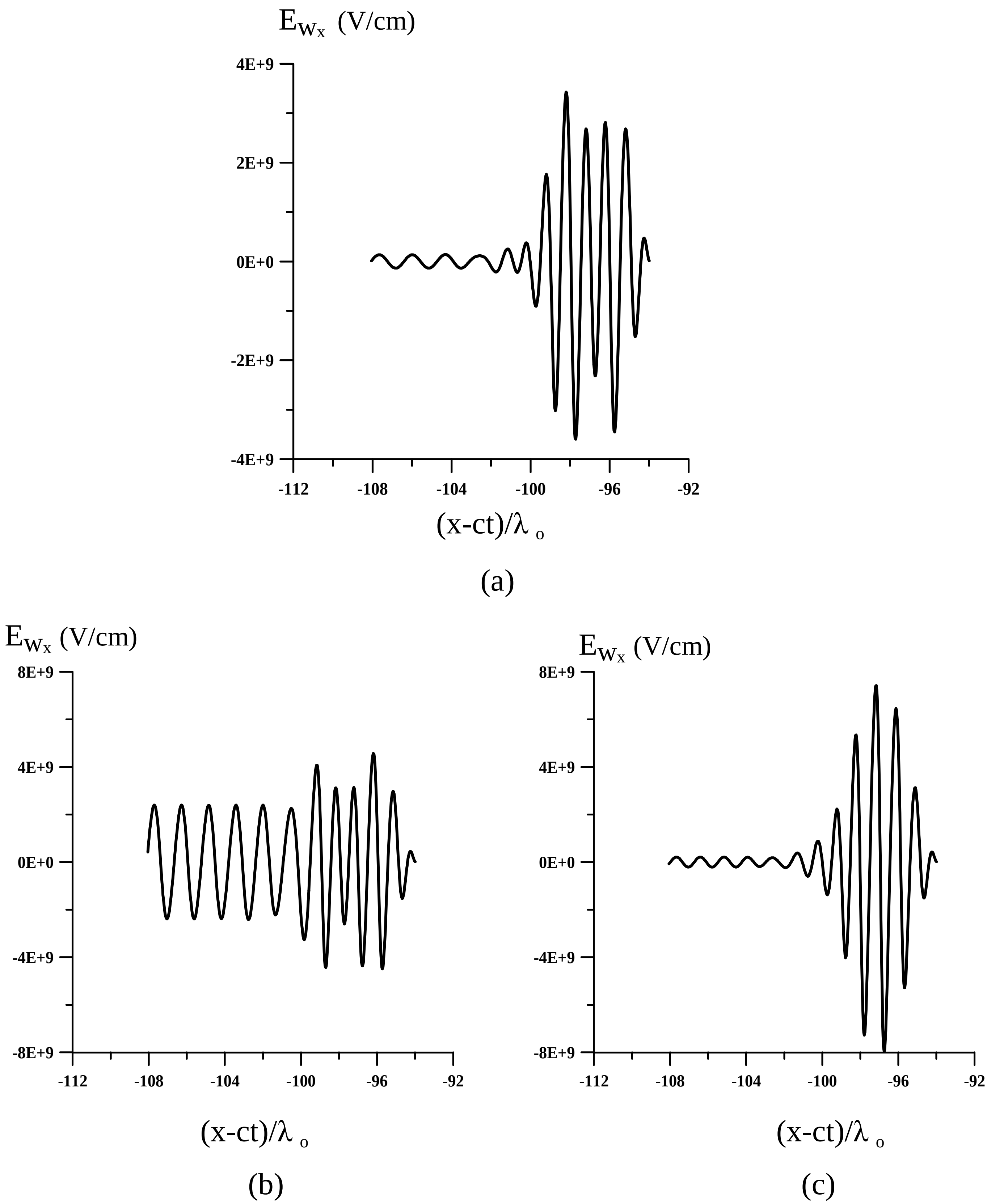

Figure (4-18) The wakefield of a laser pulse in a magnetized plasma for intensity of laser pulse $I=5x10^{15}$(W/cm^2) as a function of distance normalized by λ_o and (a) B=60 MG, (b) B=70 MG, (c) B=80 MG.

From figure (4-18), it can be noticed that the laser wakefield after the interaction decreases in value for magnetic field B=80 MG where saturation is observed. Therefore, in the present work the magnetic field B=70 MG can be considered as the best value externally applied on a plasma, since it produces the highest wakefield, hence, the highest electron acceleration as shown in table (4-7).

Table (4-7) The maximum values of wakefield during and after the interaction for I=$5x10^{15}$(W/cm^2).

B (MG)	E_W (V/cm) (during interaction)	E_W (V/cm) (after interaction)
0	2.0 $x10^9$	$3.5x10^7$
60	3.4 $x10^9$	$1.4x10^8$
70	$4.6x10^9$	$2.4x10^9$
80	$7.4x10^9$	$2.1x10^8$

From table (4-7), one can see that the maximum laser wakefield during the interaction increase to about 4 times for B=80MG compared with its value during the interaction in a non-magnetized plasma and it reaches about 50 times after the interaction for B=70 MG compared with the laser wakefield in a non-magnetized plasma.

Chapter Five

Conclusions and Suggestions for Future Work

Chapter Five

Conclusions and Suggestions for Future Work

5-1 Conclusions

The results of numerical calculations in the present work illustrate the importance of the interaction of the laser pulse with non-magnetized and magnetized plasmas as means for electron acceleration. The following conclusions can be drawn from these results:

1- In the interaction of a laser pulse with an electron at rest in vacuum, the electron is accelerated during the laser pulse propagation but after the laser pulse has passed, the velocity and kinetic energy of the electron returns to zero, i.e., there is no net acceleration gained by the electron in this case.

2- In the interaction of a laser pulse with a plasma, the electrons in the plasma are accelerated during and after the laser pulse propagation.

3- A high intensity for the laser pulse can be supplemented by applying an external magnetic field on a plasma to attain high electron acceleration. This can be considered as one advantage of using an external magnetic field in acceleration of electrons in a laser-plasma interaction.

4- The velocity, kinetic energy and wakefield in a magnetized plasma can be sustained after the interaction. This can be considered as another advantage of using an external magnetic field in acceleration of electrons in a laser-plasma interaction.

5- Altogether, the results presented in this thesis, based on the Finite Difference Method, emphasize the results of previous works, based on the particle-in-cell (PIC) technique, on the feasibility of using laser-plasma interactions to accelerate electrons and other charged particles. The results also show the feasibility of using external magnetic fields in conjunction with laser-plasma interactions to gain more electron acceleration.

5-2 Suggestions for future work

1- The acceleration of electrons with relativistic velocities as a result of interaction of a high intensity laser pulse with an overdense plasma can be considered as an extension of the present work for non-relativistic electrons in an underdense plasma.

2- The acceleration of electrons in a magnetized and in a non-magnetized plasma as a result of interaction with an electron beam instead of a laser pulse can be studied and compared with the present work.

3- The acceleration of electrons in magnetized or non-magnetized plasmas in interaction with a train of pulses or with Raman forward scattering instability can be studied in future work for the purpose of comparison with the results in the present work.

4- The two cases of electron acceleration in interaction of a laser pulse with a plasma where collisions dominate and with an inhomogeneous plasma are also worth studying in the future.

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Appendices

Appendix (A)

The oscillation force on an electron in a plasma

The electric field on an electron in the x-direction can be derived from Fig.(A-1) [43].

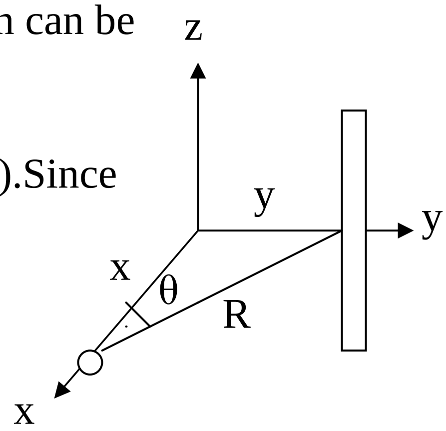


Figure (A-1) The electric field in the x-direction created between two infinite slap of charged particles.

Consider an infinite slap with charge density (σ_s).Since

$$dE_x = \frac{\sigma_s \, dy}{2\pi\varepsilon_o\sqrt{x^2+y^2}} \cos\theta \qquad (A\text{-}1)$$

where σ_s is the surface charge density.
Then,

$$dE_x = \frac{\sigma_s \, x}{2\pi\varepsilon_o\left(x^2+y^2\right)} dy \qquad (A-2)$$

Integrating, one obtains

$$E_x = \frac{\sigma_s}{2\pi\varepsilon_o}\int_{-\infty}^{\infty}\frac{x\,dy}{x^2+y^2} = \frac{\sigma_s}{2\pi\varepsilon_o}\tan^{-1}\frac{y}{x}\bigg|_{-\infty}^{\infty} \qquad (A-3)$$

or,

$$E_x = \frac{\sigma_s}{2\varepsilon_o} \qquad (A-4)$$

Consider an infinite slap with charge density ($-\sigma_s$) placed parallel in the plane x = a, the total electric field for the two slaps is:
In the case x > a

$$\vec{E}_+ = \frac{\sigma_s}{2\varepsilon_o}\vec{i} \qquad (A-5)$$

$$\vec{E}_- = -\frac{\sigma_s}{2\varepsilon_o}\vec{i} \qquad (A-6)$$

where E_+ is the electric field in the positive direction and E_- is the electric field in the negative direction.
and,

$$\vec{E} = \vec{E}_+ + \vec{E}_- = 0 \qquad (A\text{-}7)$$

In the case x < 0

$$\vec{E}_+ = -\frac{\sigma_s}{2\,\varepsilon_o}\vec{i} \qquad (A-8)$$

$$\vec{E}_- = \frac{\sigma_s}{2\,\varepsilon_o}\vec{i} \qquad (A-9)$$

and,

$$\vec{E} = \vec{E}_+ + \vec{E}_- = 0 \qquad (A\text{-}10)$$

In the case 0 < x < a

$$\vec{E}_+ = -\frac{\sigma_s}{2\,\varepsilon_o}\vec{i} \qquad (A-11)$$

$$\vec{E}_- = -\frac{\sigma_s}{2\,\varepsilon_o}\vec{i} \qquad (A-12)$$

and,

$$\vec{E} = \vec{E}_+ + \vec{E}_- = -\frac{\sigma_s}{\varepsilon_o}\vec{i} \qquad (A-13)$$

For an electron the electric field in the x-direction can be written as:

$$E_x = -\frac{\sigma_s}{\varepsilon_o} \qquad (A-14)$$

$$\sigma_s = e\, n_e\, \delta_x \qquad (A-15)$$

where n_e is the number of electrons per unit volume.

Substituting eq.(A-15) into eq.(A-14) one gets:

$$E_x = \frac{-e\, n_e\, \delta_x}{\varepsilon_o} \qquad (A-16)$$

Thus,

$$m\,\frac{d^2\delta_x}{dt^2} = e\, E_x \qquad (A-17)$$

Substituting eq.(A-16) into eq.(A-17) one gets :

$$m\,\frac{d^2\delta_x}{dt^2} = \frac{-e^2\, n_e\, \delta_x}{\varepsilon_o} \qquad (A-18)$$

And since

$$\omega_p = \left(\frac{e^2\, n_e}{\varepsilon_o\, m}\right)^{1/2} \qquad (A-19)$$

then,

$$\frac{d^2\delta_x}{dt^2} = -\omega_p^2\, \delta_x \qquad (A-20)$$

Appendix (B)

Displacement of an electron from its initial position in a magnetized plasma

The displacement of an electron from its initial position in a magnetized plasma can be derived according to Fig.(B-1) [34].

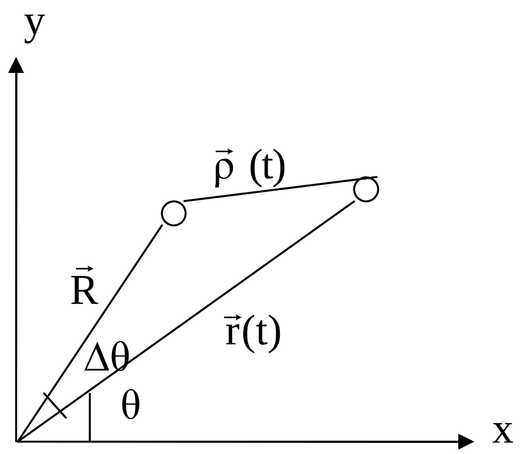


Figure (B-1) The displacement of an electron from its initial position.

since,

$$\vec{r}(t) = \vec{R} + \vec{\rho}(t) \qquad (B-1)$$

$$\therefore \ \vec{\rho}(t) = \vec{r}(t) - \vec{R} \qquad (B-2)$$

or,

$$\vec{i}\ \rho_x(t) + \vec{j}\ \rho_y(t) = \vec{i}\ r_x(t) + \vec{j}\ r_y(t) - \vec{i}\ R_x - \vec{j} R_y \qquad (B-3)$$

Then,

the displacement of the electron in the x-direction from its initial position is given as :

$$\rho_x(t) = r_x(t) - R_x \qquad (B-4)$$

where,

$$r_x(t) = x(t) \qquad (B-5)$$

However,

$$R_x = R\cos(\theta + \Delta\theta) \qquad (B-6)$$

and since $\Delta\theta$ is very small ≈ 0

$$\therefore \quad R_x = R\cos(\theta)$$

Substituting eq. (B-5) into eq. (B-4) one gets :

$$\rho_x(t) = x(t) - R\cos(\theta)$$

$$\rho_x(t) = x(t) - R\,\frac{x(t)}{\sqrt{x^2(t) + y^2(t)}}$$

Hence,

$$\rho_x(t) = x(t)\left(1 - \frac{R}{|r|}\right) \qquad (B-7)$$

The displacement of the electron in the y-direction from its initial position is given as:

$$\rho_y(t) = r_y(t) - R_y \qquad (B-8)$$

where,

$$r_y(t) = y(t) \qquad (B-9)$$

However,

$$R_y = R\sin(\theta + \Delta\theta)$$

and since $\Delta\theta$ is very small ≈ 0

$$\therefore R_y = R\sin\theta$$

or,

$$R_y = R\,\frac{y(t)}{\sqrt{x^2(t) + y^2(t)}} \qquad (B-10)$$

Substituting eqs. (B-9) and (B-10)into eq. (B-8) one gets:

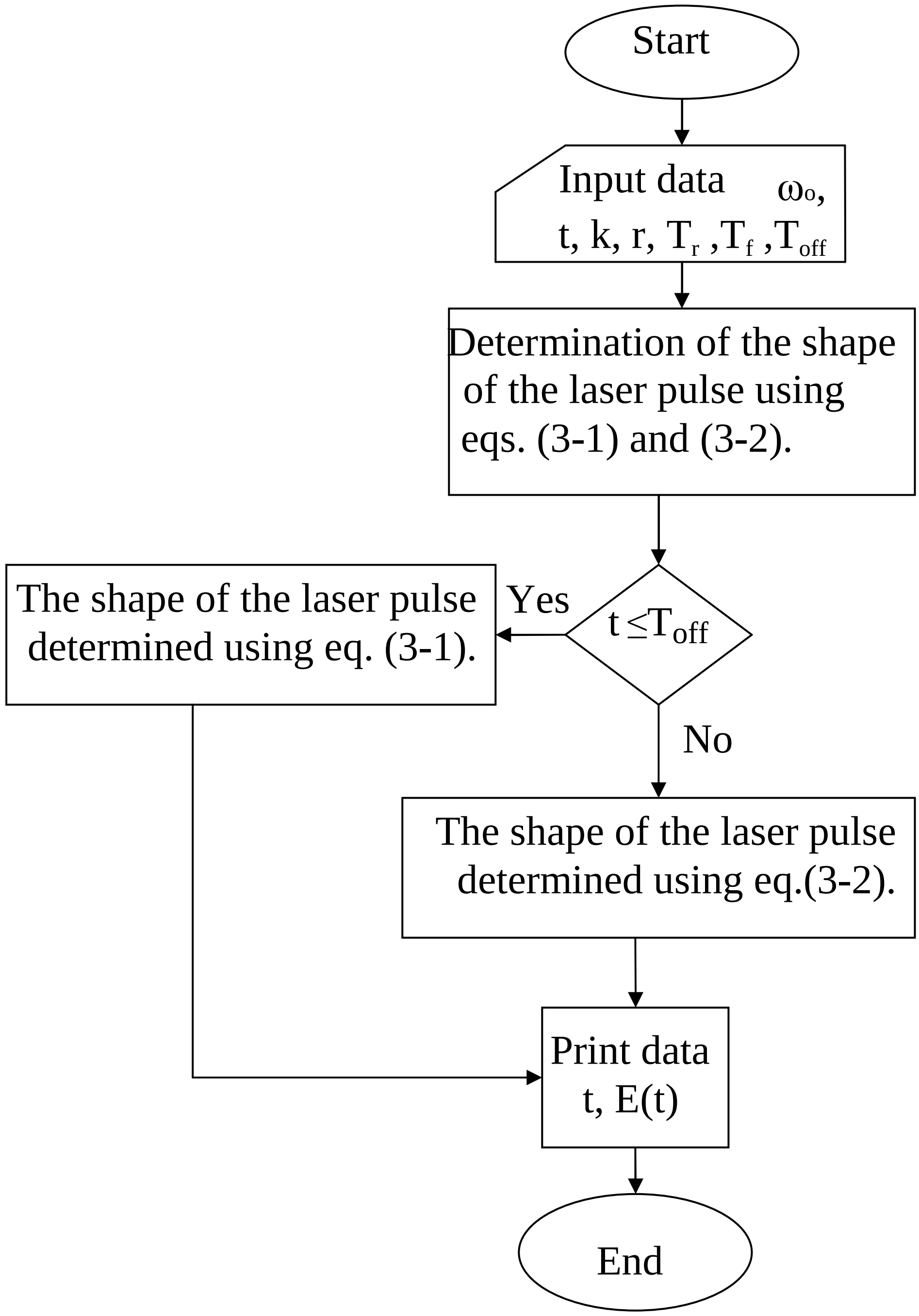
$$\rho_y(t) = y(t) - R\,\frac{y(t)}{\sqrt{x^2(t) + y^2(t)}}$$

Hence,

$$\rho_y(t) = y(t)\left(1 - \frac{R}{|r|}\right) \qquad (B-11)$$

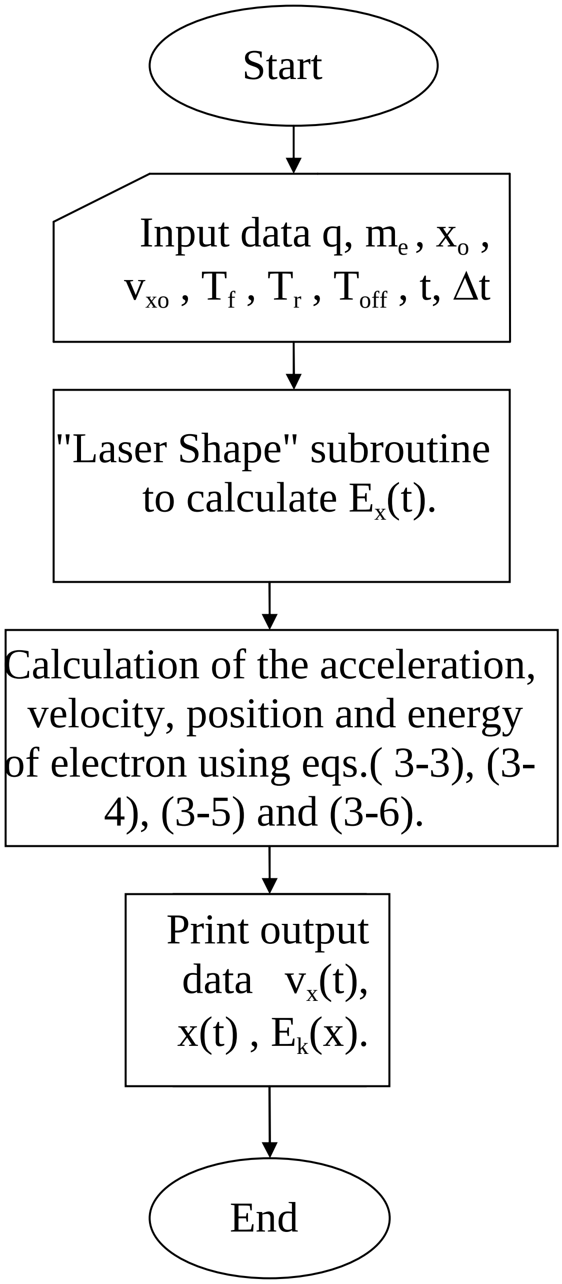
Appendix (C)

Flowchart for "Laser Shape" program



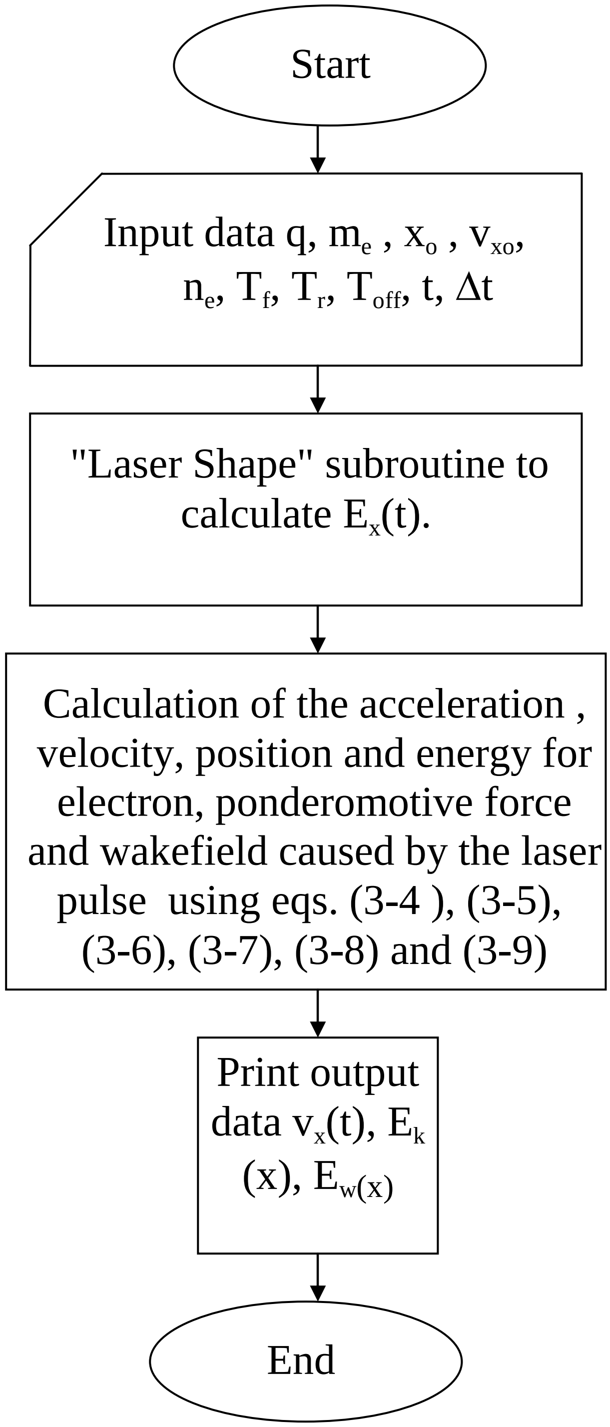
Appendix (D)

Flowchart for "Electron-Laser" program



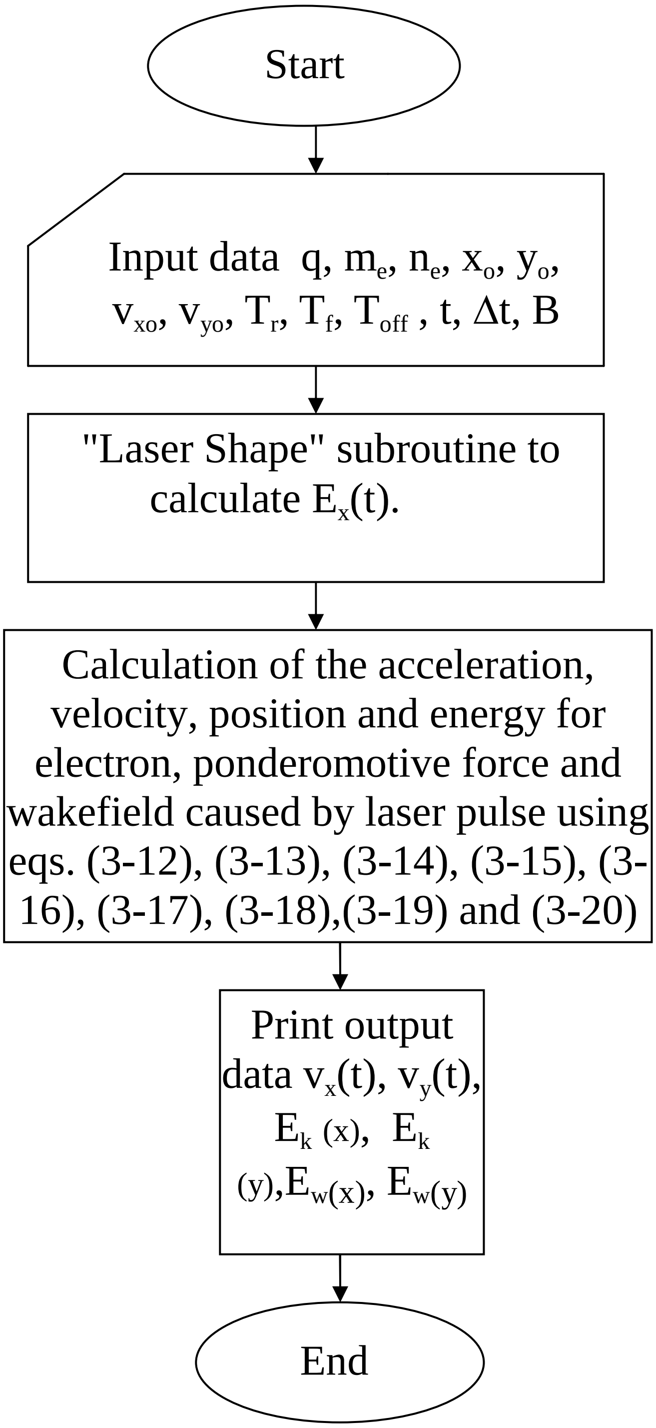
Appendix (E)

Flowchart for "Laser-Plasma" program



Appendix (F)

Flowchart for "Laser-Magnetized Plasma" program



الخلاصة

اجريت دراسة نظرية وحاسوبية في مجال تفاعل الليزر مع البلازما باستعمال طريقة الفروق المحددة (Finite Difference Method) لفهم ميكانيكية تعجيل الالكترونات عند السرع غير النسبية في البلازما اللاتصادمية .

أفترض في الدراسة الحالية في البداية تفاعل نبضة ليزر (نيديميوم-ياك) ذات فترة زمنية (25فيمتو ثانية) و شدة (5×10^{15}) (واط/سم^2) مع الكترون ساكن، وقد لوحظ تعجيل الالكترون فقط أثناء مرور موجة الليزر حيث يعود الالكترون ساكنا بعد عبور النبضة وهذا يتفق مع ماهو ملاحظ في الدراسات السابقة.

كذلك تم دراسة تفاعل نفس نبضة الليزر مع بلازما ذات كثافة الكترونية (1×10^{18} سم$^{-3}$) حيث لوحظ تعجيل الالكترون خلال التفاعل الى طاقة بحدود الكيلوالكترون فولط عند شدة نبضة ليزر تساوي(5×10^{15} واط/سم^2) بينما لوحظ تعجيل الالكترون بعد التفاعل الى طاقة بحدود (15الكترون فولط) عند نفس شدة النبضة لليزر .

واخيرا تم دراسة تفاعل نفس النبضة مع بلازما ذات كثافة الكترونية (1×10^{18}سم$^{-3}$) وبتسليط مجال مغناطيسي خارجي على البلازما وبثلاث قيم لشدة المجال هي (80,70,60 ميكا كاوس)، حيث لوحظت زيادة في تعجيل الالكترون ووصوله الى طاقة بحدود (19 كيلو الكترون فولط)عند شدة نبضة (5×10^{15} واط/سم^2) وشدة مجال مغناطيسي (80 ميكا كاوس) أثناء التفاعل في حين وصلت طاقة الالكترون الى (3 كيلو الكترون فولط)تقريبا عند شدة نبضة ليزر(5×10^{15} واط /سم^2) وشدة مجال مغناطيسي مسلط قيمتها (70 ميكا كاوس) بعد التفاعل وبعد تكون المجال الناهض لليزر بحدود (2×10^{9} فولط /سم). نستنتج من ذلك ان استخدام المجال المغناطيسي يساعد في الحصول على تعجيل عالي للالكترون والذي يمكن ان يعوض عن استخدام شدة نبضة عالية لليزر.

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دراسة تعجيل الالكترونات باستخدام تفاعل الليزر مع البلازما الممغنطة اللاتصادمية

رسالة مقدمه الى كلية العلوم في جامعه النهرين
وهي جزء من متطلبات نيل درجة الماجستير
في الفيزياء

من قبل
امال محمد كنيوي العكايشي
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