Numerical Simulation Study on the Effect of CO_2 Laser on the Plasma Behavior

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Abstract

The present work, the plasma is simulated using particle model under the action of CO_2 laser by using power density 10^{15}W per centemete^2.The behavior of the plasma is studied in three electron density regions below the critical density. The time history of the total energy, kinetic energy, and the drift energy are studied at $0.9n_{cr}$, $0.95n_{cr}$, and $0.99n_{cr}$. The results indicated that the total energy of the system slightly increases at the first time steps after that time a rapid increase in the energy are observed. The time evolution of the kinetic energy is studied, the results show that the plasma heating increases rapidly due to the acceleration of the plasma particles by the laser light. In this work the time history of the drift energy is plotted at each time step of the run.

Keywords: plasma, plasma simulation, computational physics.

Introduction

Traditionally the investigation of the behavior of complex physical systems has been carried out through the application of two well-tested techniques, namely, the experimental techniques in which one disturbs the system in some controlled manner and observes its behavior, and the theoretical approach in which one uses analytical mathematical techniques to determine the behavior consistent with well-established physical laws. In the case of large scale physical phenomena, one must often substitute observations of naturally occurring behavior for well controlled experiments. The great advances in physics have come through the combined applications of these two approaches. There are a large number of physical problems for which experiments are difficult or impossible, and the simultaneous interaction of a large number of degrees of freedom makes analytic theoretical treatments impractical. Often, however, we understand what the fundamental laws that govern the system are, but we are simply unable to work out their consequences. Most of the rich variety of natural phenomena that occur all around us are of this type. At the other extreme, we may not be sure of the physical laws. However, we may have proposed ones which we are unable to test because of the complexity of the theory. Recently, a powerful new method for both types of investigation has become possible through the advent of modern high-speed computers. This is the method of computer simulation or computer modeling. Computer simulation has become a powerful tool for the study of plasma physics. Numerical simulation of plasmas is achieved by simply computing the motion of a collection of charged particles, interacting with each other and with external applied fields. When appropriate methods are used, relatively small systems of thousand superparticles can indeed simulate accurately the collective behavior of real plasmas. The development of new algorithms and the availability of more powerful computers has allowed particle simulations to progress from simple one-dimensional, electrostatic problems to more complex and realistic situations involving electromagnetic fields in multiple dimensions and up to 106 particles [1]. Any computer simulation one, two or three- dimensional starts with some initial particle distribution, i.e. the particle positions and velocities are known. First, the electromagnetic fields are calculated from Maxwell’s equations and the forces on the particles are found using the electric and magnetic fields in Newton-Lorentz equation of motion. Then the particles are moved in a small distance and the fields due to the new particle positions and velocities are recalculated. This procedure is repeated for many time steps. Fig.(1) shows an overall scheme of the computational procedure [2].

The description above suggests that simulation should progress from as follows [3,4]:

$x \to \rho \to \varphi \to E \to F$

$X_{particle} \to \rho \quad weighting, any\ order$

$\rho_{grid} \ \to \ \varphi_{grid}$

$put\ \nabla^2\varphi = -\rho$

$into\ finite\ difference\ form\ and\ solve\ for$

φ_{grid}

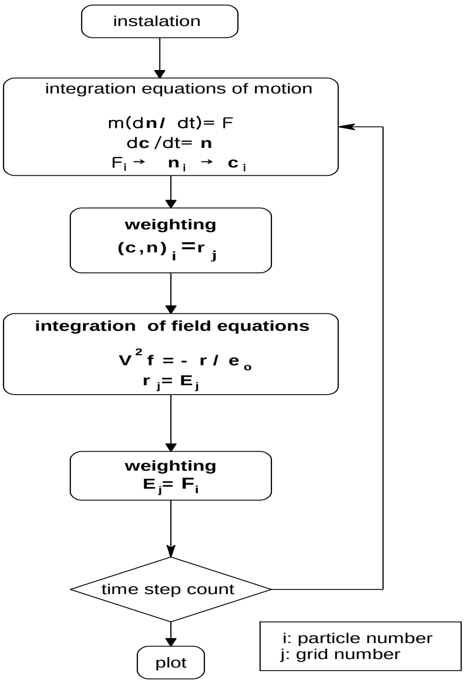

Fig. (1) Scheme of computational procedure.

$\varphi_{grid} \ \to \ E_{grid}\ put\ \nabla^2\varphi = E$

$into\ finits\ difference\ form\ and\ solve\ for \ \ E_{grid}$

$E_{grid} \ \to \ F_{particle} \ \ weighting$

The difference from laboratory plasmas is that simulations proceed discontinuously in time, step by step, using digital computation. We use a spatial grid on which the fields are calculated and a temporal grid, which is sufficiently fine to follow the plasma evolution with acceptable precision. Computer simulation for plasma may be divided into two categories: First is an MHD simulation which follows the nonlinear fluid motion of plasma in their self-consistent and applied fields. This model is useful in understanding macroscopic global scale dynamics which cannot be understood by piecewise information from individual observations. Second is a particle simulation which follows the motion of many particles in their self consistent and applied fields. Particle simulation play a significant role in plasma physics in interpreting highly nonlinear kinetic effects like wave instabilities, heating and particle acceleration. In the particle model one emulates nature by following the motion of a large number of charged particles in their self-consistent electric and magnetic fields [5-7]. Although this method sounds simple and straightforward, practical computational limitations require the use of sophisticated techniques. This need primarily arises from the limited number of particles whose motion can be followed. Even the most advanced computers cannot follow the motion of more than a few million particles for any appreciable length of time. This can be compared to the huge number of particles encountered in laboratory and natural plasmas, for this reason each particle in a simulation as representing many particles of a real plasma.

Description of the numerical model

The basic scheme of this model is very simple. First, we accumulate the charge density on the grid from particle positions and velocities. Second, we solve Poisson's equation on the grid to find the electric potential and the electric field. Finally, we interpolate the fields on the grid to the particles position and use the interpolated force on Newton's equations of motion to determine new particle positions and velocities. Then, we repeat this cycle as many time steps as necessary to study our system [8]. CIC plasma model use a spatial grid to mediate the electromagnetic interactions between particles. Charge and current densities are formed from particle coordinates onto a spatial grid. Using partial difference equations with the acceleration found by interpolation from the electric and magnetic fields on the grid. Particle pushing is done with the second-order accurate leap-frog technique as shown in Fig. (2).

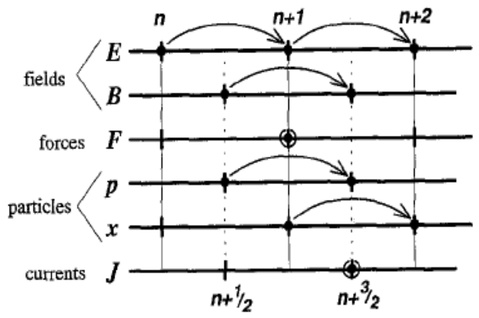

Fig.(2) Leapfrog time integration scheme.

The charge densities at all of the grid points then become the right hand side of Poisson's equation

$$\nabla^2\varphi = \rho(x,y)$$

In finite difference form, this becomes the five points form,

$$\frac{(\varphi_{j-1}-2\varphi_j+\varphi_{j+1})_k}{\nabla x^2}+\frac{(\varphi_{k-1}-2\varphi_k+\varphi_{j+1})_j}{\nabla y^2}=-\rho_{j,k}$$

The fields are located at the same points as potentials by:

$$(E_X)_{j,k}=\frac{\varphi_{j-1,k}-\varphi_{j+1,k}}{2\Delta x}$$

$$(E_y)_{j,k}=\frac{\varphi_{j,k-1}-\varphi_{j,k-1}}{2\Delta y}$$

The spatial grid, used for obtaining the fields from particle charge density and current density ,has grid points $X_J=j\Delta X$, $Y_k=k\Delta Y$, as shown in Fig. (3).

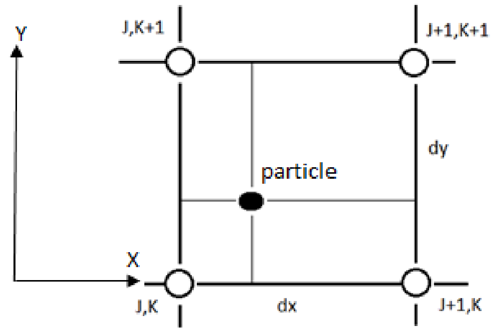

Fig.(3) Typical two dimensions rectangular grid in x,y.

Results and Discussion

The study of the time evolution of the kinetic energy, drift energy and the total energy are very valuable for understanding the behavior of the plasma under the influence of the laser light. In this work we present a two dimensional simulation program to describe some important of laser plasma interactions. The Aluminum plasma is simulated under the influence of CO_2 laser ($\lambda = 10.6\mu m$) and using power density 10^{15}W/cm^2. The behavior of the plasma is studied in three electron density regions below the critical densities; n_e=0.90n_{cr}, n_e=0.95n_{cr}, and n_e=0.99n_{cr}.The electric field of the electromagnetic radiation is linearly polarized in the y- direction and the magnetic field is polarized in the z-direction.the laser beam is traversing the plasma, accelerates the electrons due to interaction of the charge on the electrons and the electric fields in the beam. The energy will transfer from the E.M. wave to the plasma by Inverse Bremsstrahlung Absorption, where the electrons oscillating under the action of the laser light [9] and will result in higher average kinetic energy ,or temperature, of the electrons after the beam has passed through the plasma [10].

Figs. (4, 5, 6) represents the time history of the kinetic energy and the drift energy for power density 10^{15}W/cm^2 at n_e=0.90n_{cr}, n_e=0.95n_{cr}, and n_e=0.99n_{cr} under the influence of CO_2 laser. It is clear that the curves of the kinetic energy is raising slightly from time step 0 to time step 250. After that the energy curves increases rapidly until time step 900 in the case 0.90n_{cr}, 0.95n_{cr} and at time step 870 in the case 0.99n_{cr}.This reflect the fact that the plasma at the first time steps is nearly collision less, after that the plasma heating increases rapidly due to the acceleration of the plasma particles by the laser until the energy curves reaches a saturation state. As shown in Figs.(4, 5 and 6) that kinetic energy increases more rapidly than the drift energy where they are given in terms of the initial kinetic energy.

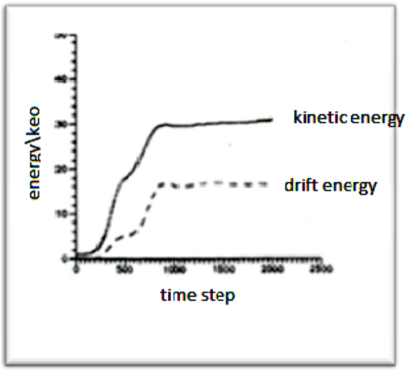

Fig. (4) Time evolution of kinetic energy drift energy at ne=0.9ncr.

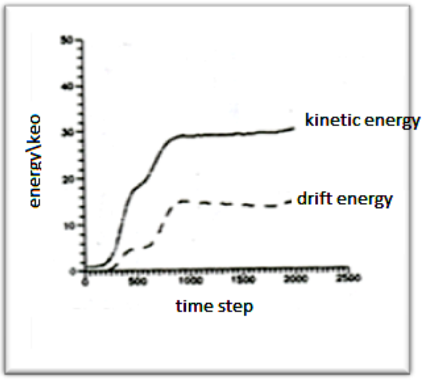

Fig. (5) Time evolution of kinetic energy and drift energy at ne=0.95ncr.

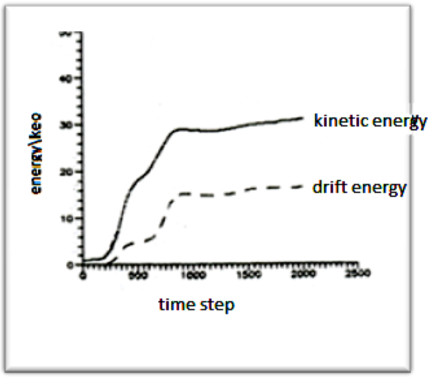

Fig. (6) Time evolution of kinetic energy nand drift energy at ne=0.99ncr.

The results are listed in Table (1). It is clear that the kinetic energy and drift energy reach saturation state at certain time steps.

Table (1)
Energy saturation of thermal energy and drift energy at different electron densities.

$n_e \backslash n_{cr}$	*kinetic energy*		*drift energy*	
	energy saturation	*time step*	*energy saturation*	*time step*
0.90	30	900	16	850
0.95	29	900	15	900
0.99	29	850	15	900

The relation between the kinetic energy and the electron density is shown in Table (2). As can be seen from this table the values of the kinetic energy are increased with increasing the electron density.

Table (2)
Thermal energy (normalized by initial kinetic keo) at different electron densities.

power density	$n_e \backslash n_{cr}$	*thermal energy at time step 500*
10^{15}w\cm^2	0.90	18.25
10^{15}w\cm^2	0.95	18.25
10^{15}w\cm^2	0.99	18.50

Figs.(7,8,9) show the temporal evolution of the total energy of the system for 10^{15}W\cm^2 power density at $n_e=0.90n_{cr}$, $n_e=0.95n_{cr}$, and $n_e=0.99n_{cr}$. The results indicated that the total energy of the system slightly increases at the first time steps, after that a rapid increase in the energy curves are observed due to the acceleration of the plasma particles by the laser light. It is clear from Fig.(7) and Fig.(8) that the energy curves from time step 0 to time step 250 are increasing slightly, after that the curves increases rapidly until time steps 1000 and 950 for $n_e=0.90n_{cr}$ and $n_e=0.95n_{cr}$ respectively. Fig.(9) gives the simulation results of the total energy at $n_e=0.99n_{cr}$. We noticed that there is no saturation sate, where the total energy will increase rapidly until time step 900, then the energy increases slightly. The saturated state is characterized by a steady transfer of the energy from the laser light to the plasma particles. The total energy are given in terms of the initial kinetic energy. Data are extracted from Figs.(7, 8, 9) and displayed in Tables (3). The table lists the values of the saturation energy and its time step. It is clear from the figs and the data tables that the curve of the total energy at $n_e=0.99n_{cr}$ do not has a saturation state.

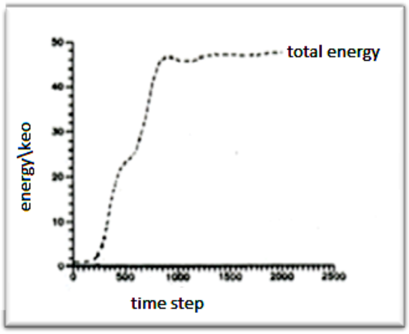

Fig. (7) Time evolution of total energy at ne=0.90ncr.

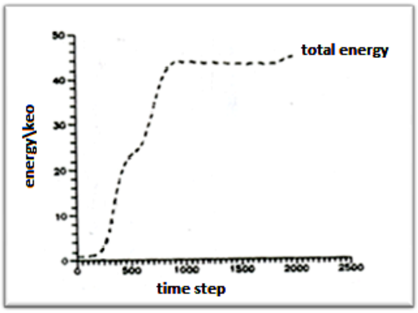

Fig.(8) Time evolution of total energy at ne=0.95ncr.

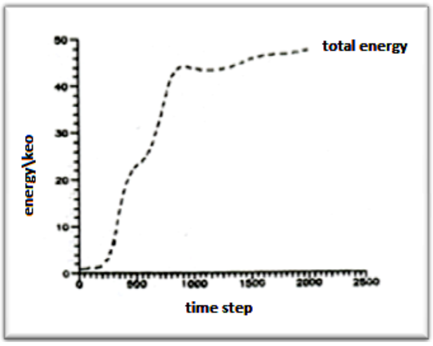

Fig. (9) Time evolution of total energy at ne=0.99nc.

To observe the relation between the electron density and its temperature, we can plot growth the thermal energy of the system at each time step, as shown in Fig.(10). This figure indicates that the plasma temperature increases at high region of the electron density. This means that the coalitional absorption process becomes efficient at that regions.

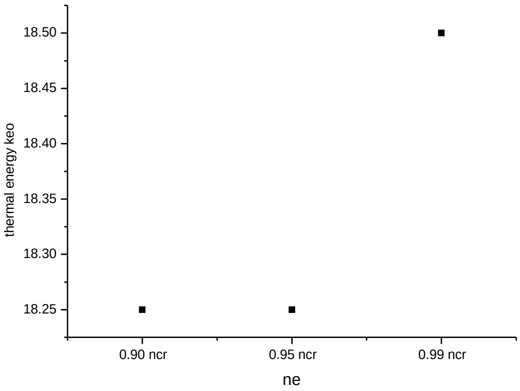

Fig.(10) Relation Between Thermal Energy and Electron Density.

Conclusion

In the present work, we have performed the numerical model based on CIC method to investigate the behavior of plasma under the influence of CO_2 laser $\lambda = 10.6\mu m$, we assumed that that the laser light propagates in the z-direction. We observed from the figs. That the energy curves at the first time steps are slightly increases, this reflect the fact that the plasma is nearly collisionless. After that the plasma heating increases rapidly until the energy reached a saturation state. The saturated state is characterized by a steady transfer of the energy from the laser light to the plasma particles. The inverse bremsstrahlung plays an important role in the heating of a plasma by laser radiation. The absorbed energy of the laser causes an increase in the kinetic energy of the electron, i.e. an increase in the electron temperature.

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الخلاصة

في هذا العمل تم محاكاة البلازما باستخدام نموذج الجسيم تحت تاثير ليزر ثاني اوكسيد الكاربون وبكثافة قدرة 10^{15}W\cm^{2} ان سلوك البلازما قد درس في ثلاثة مواقع للكثافة الالكترونية هي $n_e=0.90n_{cr}$, $n_e=0.95n_{cr}$, $n_e=0.99n_{cr}$ حيث أظهرت النتائج ان الطاقة الكلية للنظام تزداد قليلا" في الراحل الاولى للتفاعل ولاكن في المراحل المتقدمة من التفاعل تحصل زيادة سريعة في طاقة النظام بسبب عمليات الامتصاص للطاقة. تم دراسة سلوك الطاقة الحرارية وطاقة الانجراف في نفس مواقع الكثافة الالكترونية المذكورة وكانت النتائج تشير الى حصول زيادة سريعة في المراحل المتقدمة من التفاعل. النتائج اظهرت ان عملية تسخين البلازما تزداد بسرعة نتيجة زيادة تعجيل الجسيمات بواسطة اشعة الليزر. في هذا البحث تم دراسة ورسم سلوك سرعة الانجراف خلال زمن التفاعل.