Engineering and Technology Journal
Journal homepage: engtechjournal.org

Study the Effect the Laser Intensity on the Behavior of the Kinetic Energy, Drift Energy and the Total Energy of the Silver Plasma

Esam A. Tawfiq [a]

[a] University of Technology, Department of Applied Science, Branch of Applied Physics, Baghdad, Iraq, esamtawfiq123@gmail.com

Submitted: 25/11/2019 Accepted: 21/07/2020 Published: 25/12/2020

KEYWORDS

Laser plasma interaction, silver plasma, Ruby laser, plasma simulation, Particle-in-cell, inverse bremsstrahlung, saturation.

ABSTRACT

The particle-in-cell plasma simulation program in two dimensions was developed to display the properties of silver plasma under the effect of Ruby laser 694.3 nm with different intensities; 1012Wcm-2, 1015 Wcm-2, 1018 Wcm-2, and 1020 Wcm-2. The time evolution and the properties of total energy, kinetic energy, and drift energy of the system were examined in the region near the critical density (ne=0.2ncr). The charged particles respond to the laser pulse after a specified period of interaction time in the form of an increase in the energy of the system. This response depends on the intensity of the laser pulse used in this work. A significant increase was observed in plasma energy due to the efficient transfer of laser energy to plasma particles by the Inverse Bremsstrahlung process. The effectiveness of this process is reduced when the laser intensity is increased. This result is shown especially when using 1020 Wcm-2 laser intensity. The results indicated that the plotting of the electron velocity distributions during different time steps of interaction is Maxwellian and it was observed that the curves have a strong energy tail that indicates energy transfers and heating to the plasma.

How to cite this article: E.A.Tawfiq, "Study the effect the laser intensity on the behavior of the kinetic energy, drift energy and the total energy of the silver plasma," Engineering and Technology Journal, Vol. 38, Part B, No. 03, pp.142-149, 2020.
DOI: https://doi.org/10.30684/etj.v38i3B.1346

1. INTRODUCTION

Plasma simulation is an important tool used by physicists and engineers to improve the ability to understanding any complex physical phenomenon and then make it simple and explanation is possible, especially after the great development in the software and computer systems in different conditions [1]. The great advances in computer systems and programming make numerical simulations play a major role in solving many physics problems and studying some important applications. The interaction of high energy lasers with plasma leads to different kinds of important applications; plasma heating [2, 3], including high-harmonic generation [4-6], soft x-ray lasers [7, 8], and laser-driven particle accelerators [9-12]. Through the past 30 years, researchers have a great deal of theoretical and computational work on the interaction and propagation of short-pulse laser through the plasmas [13-16]. From a physical point of view, the inverse bremsstrahlung process dominates the absorption of plasma particles to the laser energy [17, 18]. The interactions of high power lasers with plasma have opened an important area for many applications that have stimulated scientists to understand the nature of these interactions. The physical mechanisms of electron accelerations depend on the properties of laser pulse; intensity, pulse duration, wavelength, beam quality and, plasma together; temperature, electron density measurements, ionization, and plasma formation processes [19]. Specific methods are available to exchange the energy of the laser to the plasma among them are collisional absorption (or inverse bremsstrahlung), resonance absorption, and vacuum heating [20-23]. Intensities, $I < 10^{15} Wcm^{-2}$, the collisional absorption mechanism is usually happening via direct collisions, where plasma particles such as electrons, ions, or neutrals collide directly with each other and consequently the energy can be transferred which leads to the plasma heating. Resonance absorption and vacuum heating is strongly promoted at higher intensities near the critical density [24]. The study of plasma properties by numerical methods gives a comprehensive form of plasma formation and evolution over time iteration. Different numerical methods are used to describe the form of the physical system of the plasma which is a kinetic approach or a fluid approach [21]. The first involves following the movement of individual particles, which requires solving the motion equations to determine the locations and velocities of the particles, and the simulation particles jump to new positions according to the forces acting on them. In the fluid approach, the collective behavior of particles is used and the plasma is studied using the equations of continuity and momentum that describe particle density and velocities as a collection. In this project, the plasma is treated as an ensemble of computational particle that represents thousands of real particles electrons or ions and it behaves the same as real plasma particles and in it their charge to mass ratio is the same. The computational particle has a finite size in which the charge of a particle is distributed over a finite area as shown in figure 1, these particles pass freely through each other without any change in its shape or the internal motion. The finite-size particle reduces numerical noise from the discrete of the spatial grid, therefore, the importance of this technique is that it is inexpensive and faster computationally [25].

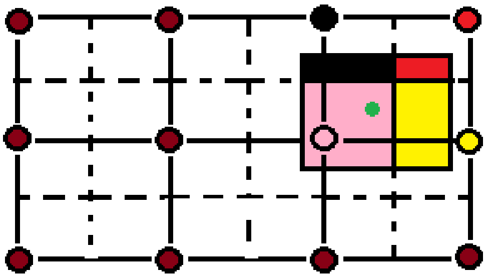

Figure 1: Schematic of computational mesh, distributed charge of the particle among the surrounding grid points

The full description of the plasma through a numerical program have a sequence of operations which are repeated at each time step as shown in figure 2 as follows[26,27]:

1-Assign charge particle to the grid points by linear weighing.
2-Solve Poisson’s equation on the grid points.
3-Compute forces from the grid values and interpolates forces at particle positions.

At each time step, the equations of motion for the electrons are solved by iteration and the electric field is found from a solution of Poisson's equation. The ions are a uniform neutralizing background

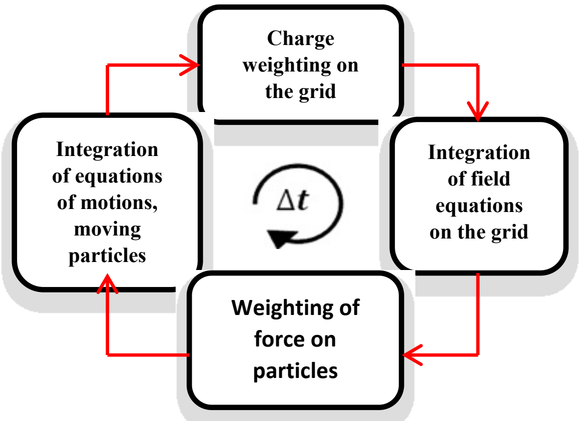

Figure 2: Time evolution of plasma by PIC model

2. NUMERICAL TECHNIQUE

Numerical simulation has become a very important tool for examining the properties of plasma, especially in the laser-produced plasma, because the mathematical equations that describe the system are often difficult to solve by analytical methods. These systems are described by several techniques, including the particle-mesh method [28]. Currently, for this project, we developed a two-dimensional particle-in-cell code by using finite-difference mesh techniques. The simulation program was written by Fortran Language 99, where the best option for solving the kinetic equations of plasma that correspond to the evolution of computers at present is "particle simulation". The program begins with some initial conditions of the system involves several thousand charged particles moves in both self – consistent and electromagnetic fields. In this paper, the system contains 20000 charged particles considering that the velocity distribution is a Maxwellian distribution where the computational particles moving through a spatial grid within self-consistent fields and applied external electromagnetic field. The space and time under consideration are treated as discrete rather than continuous [29].

The particle positions are used to explore the charge densities on mesh points using the area weighting method. The electric field is obtained at the same mesh points of the grid from Poisson's equation, which is solved by a fast Fourier transform (FFT) method. We divided the phase space into a number of cells 64at x and y- directions, where the lengths are equal (dx=dy). On the other hand, the total time of the simulation program decomposes to numbers of small-time step (dt), so that the total time is n×dt. We consider that the temporal evolution of the plasma system energy that contains 20000 particles is confined within the computational box until the end of iterations. In this paper, the simulation box has 64×64 grid points. In this technique, we consider uniform, periodic, and one-species plasma (electrons), and the ions are treated as a fixed neutralizing background. We assume that the ions are a uniform neutralizing background. The main feature of the particle simulation is that they act like point particles in large distances where the influence of Coulomb's power appears, while the behavior of these particles varies when the distance between them decreases to get overlap and the force begins weaker than the corresponding Coulomb force[28].

3. RESULTS AND DISCUSSION

This paper explores the effects of laser energy intensity on the plasma system at region $n_e=0.2n_{cr}$ and the ratio between laser frequency w_o and electron plasma frequency w_o/w_{pe} is 2.24. The time evolution of the kinetic energy, drift energy and the total energy of the particles are examined.

Figure (3) shows the temporal evolution of the kinetic energy of particles in the case of 10^{12} Wcm^{-2}. The results showed that the process of energy exchange between laser and plasma can be observed as a result of the increase in kinetic energy after 200-time steps from the beginning of the interaction. The figure shows that the energy transfer process is efficient between $200 < w_{pe}\times dt < 1250$. This means that the electrons during this part of the time period are accelerated to high energy via collisional absorption process which plays an essential role in transferring the laser energy to the plasma.

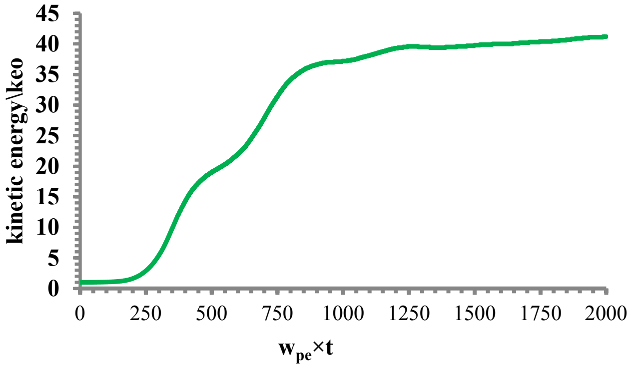

Figure 3: Time evolution of the kinetic energy at $n_e=0.2n_{cr}$, z=47, $w_o=2.24w_{pe}$,694.3nm,

In this situation, laser energy is transferred to the plasma particles by columbic interactions, generally in electron-ion collisions. The study of variation of plasma kinetic energy during the time duration of interaction gives us important information about the absorption behavior. The transfer of energy to the plasma particles by collisional absorption is very effective up to 1250 time steps, after that time energy transfer is reduced, and the collisional absorption efficiency decreases and the appearance of a saturation state. The saturation state takes place after 52% of the simulation time. Figures 4-6, provide the temporal development of the kinetic energy of the plasma when the laser pulse intensity increases (10^{15}, 10^{18}, 10^{20}W/cm^{-2}) and by using the same conditions for plasma and laser. The results showed that the curve of kinetic energy with time when increasing the intensity of the laser pulse takes similar behavior in the previous case where the kinetic energy increases with time until the saturation state.

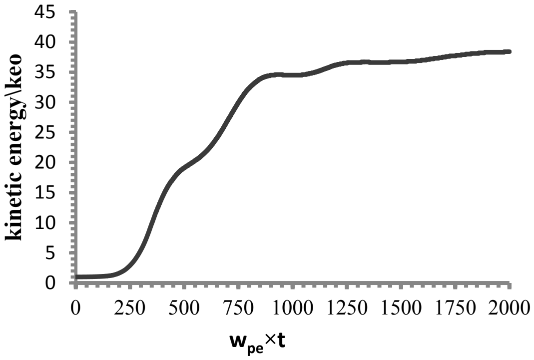

Figure 4: Time evolution of the kinetic energy at $n_e=0.2n_{cr}$,z=47,,$w_0=2.24w_{pe}$,694.3nm,10^{15} Wcm^{-2}

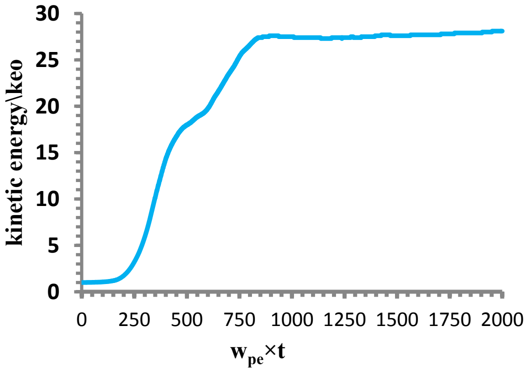

Figure 5: Time evolution of the kinetic energy at $n_e=0.2n_{cr}$,z=47, $w_0=2.24w_{pe}$

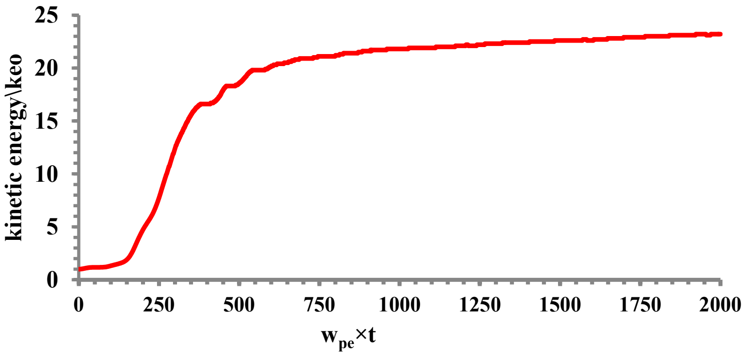

Figure 6: Time evolution of the kinetic energy at ne=0.2ncr,z=47, 694.3nm, $w_o=2.24w_{pe}$, 10^{20}Wcm^{-2}

For high power intensity 10^{20} Wcm^{-2} the saturation state takes place after 37% of simulation time (as seen in Figure.6). The Saturation state of the laser absorption is due to the total reflection of the laser light from the hot plasma [30]. Table 1 lists the maximum plasma kinetic energy values and the laser energy density used in the measurement taken from the above figures.

TABLE I: Laser power density and Max. kinetic energy

Power density (w/cm^2)	Max. kinetic energy / k_{eo}
10^{12}	40
10^{15}	37
10^{18}	27
10^{20}	20

In Figure 7 the plot of the time history of the drift energy was examined. These runs used 20000 simulation particles, 64×64 cells, and 10^{20} Wcm^{-2}. The figure produces unstable random movement and unstable drift speeds. Drift values are increasing slightly after 250-300 time steps and reach to the saturation state after 750 - time steps.

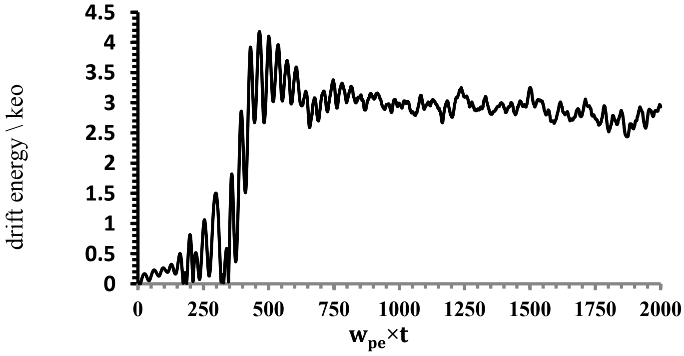

Figure 7: Time evolution of the drift energy at $n_e=0.2n_{cr}$, z=47, $w_o=2.24w_{pe}$, 694.3 nm, 10^{20} wcm^{-2}

Figure 8 demonstrates the growth of kinetic energy of the plasma over 2000 time steps under the influence of different values of laser density. For 10^{12}Wcm^{-2} and 10^{15} Wcm^{-2} the kinetic energy begins to increase linearly after 250-time steps until the saturation state after 1250- time steps. In this case, reaching saturation state took 62.5% of the total iteration time. For 10^{18} Wcm^{-2}, the general behavior is similar but the maximum kinetic energy values decreased and the saturation process appears after 850- time steps (42.5% from the total iteration time). It can be seen that by using higher power intensity (10^{20} Wcm^{-2}), the Electrons are accelerated rapidly and the maximum electron kinetic energy get to saturation within a short period of time up to20% of the iteration time.

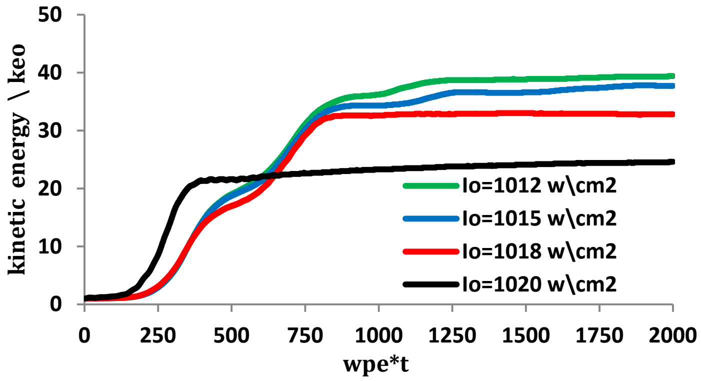

Figure 8: Time evolution of the kinetic energy at different power densities , ne= 0.2 ncr,wo=2.24wpe

Figure 9 shows the time history of the total energy, kinetic energy, and drift energy. These run used 10^{20} Wcm^{-2} of laser intensity, n_e=0.2ncr and w_o=2.24w_{pe}.The results showed that the kinetic energy and drift energy form 92% and 12%% of the total energy respectively.

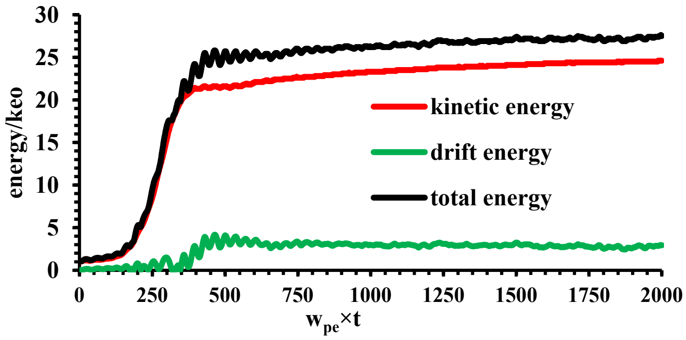

Figure 9: Time evolutiom of total ,kinetic and drift energy (n_e=0.2n_{cr} , w_o=2.24$w_{pe,}$, Io =$10^{20}$$Wcm^{-2}$

4. CONCLUSION

The main idea of this paper is to study plasma energies relative to laser intensities at a region near the critical density (n_e=0.2n_{cr}. The effect of laser intensity on the absorption rate has been investigated.

The temporal evolution of the kinetic energy, thermal energy, and the total energy of the particles using the PIC method was examined with w_o=2.24w_{pe}. In this study, Inverse Bremsstrahlung (collisional absorption) is a dominant process that can be defined as the absorption of electromagnetic radiation by an electron making Coulomb collisions with ions, which increases the kinetic energy of the electron and hence its temperature. By increasing the laser intensity, we experience a decrease in the maximum of total energy, kinetic energy; drift energy. In the case of increased laser intensity, the plasma absorption of laser energy will be reduced due to a decrease in the importance of collisions resulting from collisional absorption.

Acknowledgments

I would like to thank the Department of Applied Sciences at the University of Technology to provide the necessary supplies that helped to complete the project, and I would like to thank all colleagues in the department for their assistance to this work.

References

[1] J. M. Dawson, “Computer modeling of plasma: Past, present, and future,’’ Physics of Plasmas, vol. 2, no. 6, pp. 2189,1995.

[2] D.W. Forslund, J.M. Kindel, W.B. Mori, C. Joshi and J. M. Dawson, “Two-dimensional simulations of single-frequency and beat-wave laser-plasma heating’’ Physical Review Letters, vol. 54, pp.558–561, 1985.

[3] K-C. Tzeng, W.B. Mori. “Suppression of electron ponderomotive blowout and relativistic selffocusing by the occurrence of Raman scattering and plasma heating,” Physical Review Letters , vol. 81, pp.104– 107, 1998.

[4] S. Banerjee, A. R. Valenzuela, R. C. Shah, A. Maksimchuk, and D. Umstadter, “High harmonic generation in relativistic laser–plasma interaction,” Physics of Plasmas, vol. 9, pp. 2393,2002.

[5] S. Tang, N. Kumar, and C. H. Keitel, “Plasma high-order-harmonic generation from ultraintense laser pulses,” Phys. Rev. E vol.95, no. 5, pp. 051201, 2017.

[6] J. T. Mendonça and J. Vieira,“ High harmonic generation in under dense plasmas by intense laser pulses with orbital angular momentum,” Physics of Plasmas, vol. 22, pp.123106, 2015.

[7] R. Viskup," High energy and short pulse lasers, ” Intech Open, 2016.

[8] A. Bartnik, “Laser-plasma extreme ultraviolet and soft X-ray sources based on a double stream gas puff target: Interaction of the radiation pulses with matte,” Opto-Electronics Review, vol. 23, pp.172-186, 2015.

[9] D. A. Jaroszynski, R. Bingham and R. A.Cairns, “Laser-Plasma Interactions,” CRC Press, 2017.

[10] T. Tajima, J.M. Dawson, “Laser Electron Accelerator,” Physical Review Letters, vol. 43, pp.267–270, 1979.

[11] P. Mora, T.M. Jr. Antonsen ,“ Kinetic modeling of intense, short laser pulses propagating in tenuous plasmas,” Physics of Plasmas, vol. 4, pp. 217–229,1997.

[12] A.A. Andreev, J. Limpouch , “ Ion accelerate on in short-pulse laser–target interactions,” Journal of Plasma Physics, vol. 62, pp.179–193,1999.

[13] T. Antonsen and P. Mora, “Self-focusing and Raman scattering of laser pulses in tenuous plasmas,” Physical Review Letters , vol. 69, pp. 2204,1992.

[14] P. Sprangle, E. Esarey, J. Krall, and G. Joyce, “ Propagation and guiding of intense laser pulses in plasmas,” Physical Review Letters , vol. 69,pp. 2200,1992.

[15] J. Krall, A. Ting, E. Esarey, and P. Sprangle, “ Enhanced acceleration in a self-modulated-laser wake-field accelerator,” Physical Review E, vol. 48, pp. 2157,1993.

[16] W. B. Mori, C. D. Decker, D. E. Hinkel, and T. Katsouleas, “Raman forward scattering of short-pulse high-intensity lasers,” Physical Review Letters, vol. 72, pp.1482, 1994.

[17] S. Pfalzner, “ Influence of strong laser fields on the inverse bremsstrahlung collision frequency,” Applied Physics B, vol. 55, pp. 368-372,1992.

[18] H.-J. Kull and L. Plagne, “ Quantum-mechanical dielectric model of the electron–ion collision frequency in strong laser fields,” J. Physics of Plasmas, vol. 8, pp.5244-5256, 2001.

[19] M. Mahdavi and S. F. Ghazizadeh,“ Linear Absorption Mechanisms in Laser Plasma Interactions,” Journal of Applied Science, vol.12,pp.12-21,2012.

[20] P. Mulser and D. Bauer, “High Power Laser-Matter Interaction,” Springer, Berlin, Heidelberg 2010.

[21] L. K. William, “The Physics of Laser Plasma Interactions,” 1st, Addison-Wesley, New York, 2003.

[22] S. Eliezer, “The Interaction of High-Power Lasers with Plasmas,” Publishing, Bristol, Institute of Physics, Bristol, England, 2002.

[23] T. Bornath, M. Schlanges, P. Hilse, and D. Kremp, “Nonlinear collisional absorption in dense laser plasmas,”Phys. Rev. E, vol. 64, pp. 26414,2001.

[24] S. Z..Ming, W. S.Ming, Y. Lu-Le, W. Wei-Min,C. Yun-Qian, C. Min and Z. Jie, “Absorption of ultrashort intense lasers in laser–solid interactions,” Chinese Physics B, vol. 24, no. 1, pp. 015201, 2015.

[25] K. Germaschewski, W. Fox, S. Abbott, N. Ahmadi, K. Maynard, L. Wang, H. Ruhl, A. .Bhattacharjee,” The Plasma Simulation Code: A modern particle-in-cell code with patch-based load-balancing,” Journal of Computational Physics, vol. 318, pp.305-326, 2016.

[26] I. I. Ewa, U. S. Aliyu, U. S. Aliyu, A.O. Samuel, L.M. Sanusi,“Particle-in-cell simulation of electrostatic plasma in one dimension,” Arch. Appl. Sci. Res., vol. 6 , no.4, pp. 143-156, 2014.

[27] R.W.Hockney and J.W.Eastood "Computer Simulation Using Particles," Iop publishing Ltd, 1st ,1988.

[28] C. K. Birdsall and A. B. Langdon, "Plasma physics via computer simulation," Adam Hilger Bristol, Philadelphia and New York,1991.

[29] Z. Jia-tai, L. Zheng-qiang, C. Tie-qiang, W.Shi-hong, X.Lin-bao, Z. Shu-gui, T. Yin-xue and L.Xiu-qin, "Relativistic Cloud-In-Cell Simulation of Free Electron Laser," Communications in theoretical physics, vol. 13, no.4,pp.543-548,1990.

[30] S. Amoruso, M. Armenante, V. Berardi, R. Bruzzese and N. Spinelli,"Absorption and saturation mechanisms in aluminum laser ablated plasmas," Applied Physics A, vol. 65, pp. 265–271, 1997.