

Investigation of Interaction of Femtosecond Laser Pulse with Atomic Cluster of Ar in Nano-Plasma Model

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Abstract

The purpose of this research is to study the interaction of femtosecond laser pulses with atomic clusters of Ar. Hot and high-energy electrons, high charge state of ions and X-ray photons are the production of the interaction. These products are the result of ionization, heating and expansion of the cluster that is described with nano-plasma model. Numerical simulation of this work is done by particle in cell (pic) method. To investigate the influence of the shape of the laser pulse, the laser pulse is used as a secant hyperbolic. The evolution of the field inside the cluster, electron energy, ion charge state, ion and electron density of the cluster for the various intensity are calculated. The results agree well with the experimental findings.

Keywords: Charge State, Cluster, Femtosecond Laser, Hot Electron, Nano-Plasma

1. Introduction

With the development of ultra-short laser by using pulse amplification and the invention of Chirped Pulse Amplification (CPA)¹ Laser intensity can be raised to 10^{18} W/cm². This pulses can be entered into different types of plasma and create relativistic beam of accelerated electrons and protons to mega-electron volts², hard X-rays and other particles. Ponderomotive force of laser accelerates electrons in a short time interval to very high energy. In recent years considerable progress has been made in increasing energy and quality of electron beam^{3,4}. Recently clusters as an interesting target have been considered for laser plasma interaction compared to gaseous and solid targets. A target cluster is made by high-pressure gas nozzle shows important properties such as electron density solid-like in some places but the average density of clusters is low. Transmission distance in cluster is longer than the distance of the gas target. As well as, absorbed the laser energy is larger than the solid targets⁵.

The most important thing, the transfer of laser energy into matter is one of the most important issues in this matter. Acceleration of particles in laser plasma interaction is the important application of high intensity lasers with short life time. Low price and low space at the laser-plasma accelerators compared with other accelerators has led to more attention to this type of accelerator. Applications of energetic ions accelerated by the laser are fast ignition at inertial confinement fusion⁶, radiography with ion beams⁷ and nuclear physics⁸. Optimization and control of this new source of energetic ions with different applications the efforts of researchers around the world arouses to accelerate energetic ions produced by the interaction of high power lasers.

In this paper, laser pulse as a secant hyperbolic, radius of clusters of argon 150 Å and the intensity of the laser about 10^{14} W/cm² are considered. This interaction is simulated in the nano-plasma model by a particle in cell. Finally, the evolution of electron energy, ion charge state, ion and electron density of the

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cluster for different laser intensities have been studied.

2. Nano-plasma Model

There are several models to describe the interaction of the laser with atomic clusters such as the coulomb explosion model⁹, the ionization ignition model¹⁰, the inner shell excitation¹¹ and nano-plasma model^{12,13}. The best model to explain the interaction is nano-plasma model that is provided by Dytmayr and et al¹². The numerical model successfully are consistent with experimental results. In this model, the cluster ionization and heating occurs in the laser field. Thereinafter the cluster has expanded rapidly and leading to the production of energetic electrons and ions.

2.1 Cluster Ionization

Ionization of the cluster begins when the rising edge of the laser pulse reaches the cluster and releases a small number of electrons. This is called the tunnel ionization and the rate of tunnel ionization is given by¹⁴

$$W_{ADK} = \omega_a \frac{(2l+1)(l+|m|)!}{2^{|m|}|m|!(l-|m|)!} \times \left(\frac{2e}{n^*}\right)^{n^*} \frac{1}{2\pi n^*} I_p \left(\frac{2E}{\pi(2I_p)^{3/2}}\right)^{1/2} \times \left(\frac{2(2I_p)^{3/2}}{E}\right)^{2n^*-|m|-1} \exp\left[-\frac{2(2I_p)^{3/2}}{3E}\right] \quad (1)$$

The constant e is Euler's number, ω_a is the atomic frequency ($\omega_a = 4.13 \times 10^{16} \text{ s}^{-1}$),

$n^* = Z[2I_p]^{-1/2}$ is the effective principal quantum number, E is the field of the laser, and I_p is the ionization potential of the charge state in atomic units. Released electrons collide with atoms in the cluster and leading to collisional ionization that which rate of this ionization is calculated by the Lotz equation¹⁵

$$W_{inz}^{cl} = n_e S \exp\left(-\frac{\Delta\epsilon}{kT_e}\right). \quad (2)$$

Here $\Delta\epsilon(Z, T_e, n_e)$ is the shift of the ionization energy and S is the collisional ionization rate coefficient that is given by

$$S = 6.7 \times 10^{-7} \sum_{i=1}^N \frac{a_i q_i}{T_e^{3/2}} \times \left(\frac{1}{P_i/T_e^{P_i/Te}} \int \frac{e^{-x}}{x} dx - \frac{b_i \exp c_i}{P_i/T_e + c_i} \int \frac{e^{-y}}{y} dy \right) \quad (3)$$

Where P_i is the binding energy of electrons in the i th shell, q_i is the numbers of equivalent electrons in the i th sub-shell and a_i, b_i, c_i are constants. Oscillation of the produced electrons by the laser field leading to another ionization which rate of this ionization is given as follows¹⁶

$$W_{las} \approx n_e \frac{a_i q_i}{2\pi I_p m_e^{1/2} U_p^{1/2}} \left\{ \left[3 + \frac{I_p}{U_p} + \frac{3}{32} \left(\frac{I_p}{U_p} \right)^2 \right] \times \ln \left[\frac{1 + \sqrt{1 - I_p / 2U_p}}{1 - \sqrt{1 - I_p / 2U_p}} \right] - \left(\frac{7}{2} + \frac{3I_p}{8U_p} \right) \times \sqrt{1 - I_p / 2U_p} \right\} \quad (4)$$

Hence the total rate of ionization is equal to

$$W = W_{ADK} + W_{inz}^{cl} + W_{las} \quad (5)$$

From results of this study and previous research clear that dominant ionization is collisional ionization. In Figure 1, the ionization rate of three proposed mechanisms for clusters of argon ($\text{Ar} \rightarrow \text{Ar}^+$) is shown.

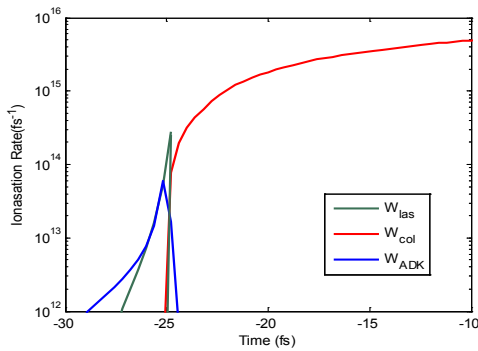


Figure 1. Rates of tunnel ionization (W_{ADK}), collisional ionization (W_{col}) and laser-assisted ionization (W_{las}) for $Ar \rightarrow Ar^+$ during the short period of field enhancement. $I = 4.0 \times 10^{14} \text{ W/cm}^2$, $\lambda = 800 \text{ nm}$ and $\tau = 40 \text{ fs}$.

2.2 Cluster Heating

Since it is assumed that there is no temperature gradient in the cluster heating from laser to be uniformly applied on the cluster. Primarily the laser gives its energy to the free electrons in the cluster by reverse sweep Brmshtlang mechanism. Exchange energy per unit volume is given by¹⁷

$$\frac{\partial U}{\partial t} = \frac{\omega}{8\pi} \text{Im}[\varepsilon] |E|^2 \quad (6)$$

Since the field within the cluster is equal to

$$E = \frac{3}{|\varepsilon + 2|} E_0 \quad (7)$$

Here E_0 is laser field outside the cluster and ε is dielectric constant of the plasma which it can be calculated from Drude equation

$$\varepsilon = 1 - \frac{\omega_p^2}{\omega(\omega + i\nu)} \quad (8)$$

Where ω_p is the plasma frequency and ν is the electron-ion collision frequency. Finally, the cluster heating rate can be calculated from the following equation

$$\frac{\partial U}{\partial t} = \frac{9\omega^2\omega_p^2\nu}{8\pi} \frac{1}{9\omega^2(\omega^2 + \nu^2) + \omega_p^2(\omega_p^2 - 6\omega^2)} |E_0|^2 \quad (9)$$

2.3 Cluster Expansion

Cluster expansion in the nano-plasma model occurs due to the two pressure. Coulomb pressure is due to repulsion of the ions in the cluster which is determined by the following equation¹⁸

$$P_{coul} = \frac{Q^2 e^2}{8\pi r^4} \quad (10)$$

Here r is the radius of the cluster. And hydrodynamic pressure as a result of the expansion of the hot electrons which is given by the following equation

$$P_e = n_e k T_e \quad (11)$$

Where k is the Boltzmann constant, T_e is the electron temperature and n_e is the electron density.

3. Result

In this paper, laser pulse is as a secant hyperbolic, radius of clusters of argon is $150 \text{ \AA}$ and the intensity of the laser is about 10^{14} W/cm^2 . The evolution of the field inside the cluster according to the Drude model shown in Figure 2.

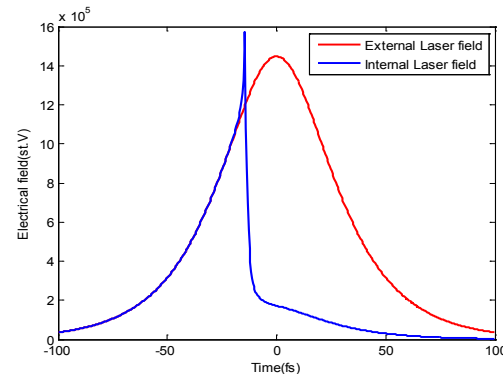


Figure 2. Electric field inside the cluster.

It is clear from Figure 2 that at the beginning the interior and exterior field are the same. With increasing charge density in the cluster internal field increases. This occurs when the electron charge density is three times the critical density ($n_e = 3n_{crit}$). Time evolution of electron energy for different laser intensities is shown in Figure 3.

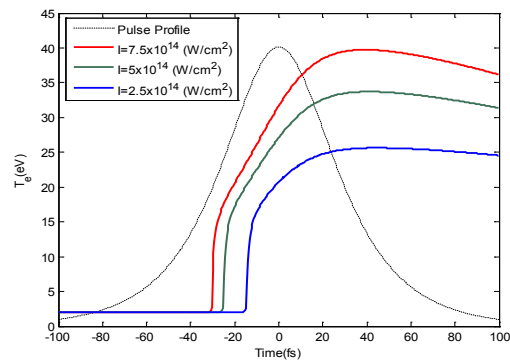


Figure 3. The evolution of electron energy for different laser intensities.

It can be seen that at higher intensities energy electrons is higher and transfer energy to electrons done sooner. Figure 4 shows the time evolution of the ion charge states of the cluster for different intensities of laser. Obviously, when the laser intensity increases, ions with high charge are produced that plays significant role in nuclear applications. It can be seen from Figure 5 that the density of cluster ions due to cluster expansion, acceleration of ions and their escape from the cluster is declining. And by increasing the laser intensity cluster expansion increases and more ions ejected from the cluster and ion density is lower.

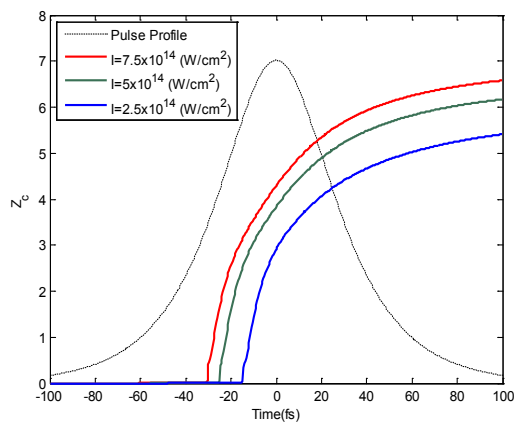


Figure 4. The evolution of the ion charge states of the cluster for different intensities of laser.

It is clear from Figure 6 that with the passage of small time and due to the ionization mechanism electron density is increasing but after a while because of the exit of electrons from the cluster number of the electrons is reduced. By increasing the laser intensity the electron density is increasing.

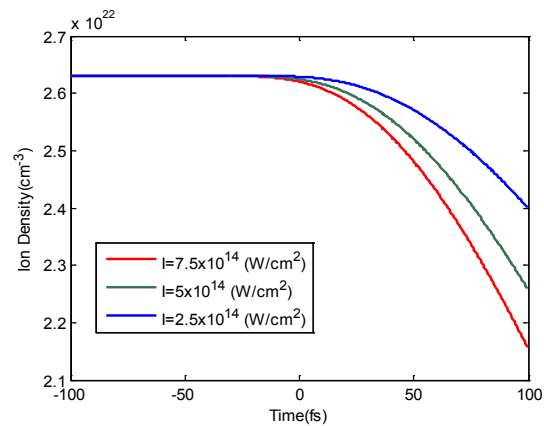


Figure 5. Time evolution of the ion density of the cluster at different intensities of laser.

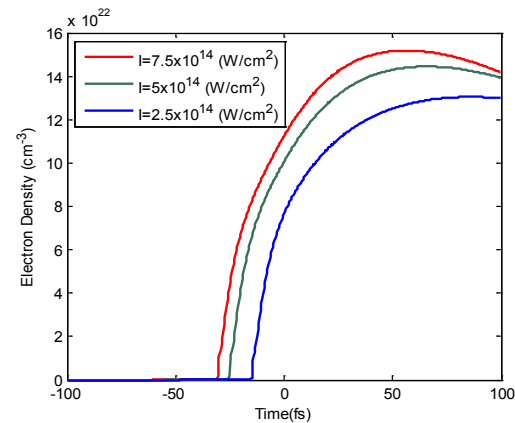


Figure 6. Time evolution of the electron density of the cluster at different intensities of laser.

4. Conclusion

According to the simulation results of interaction laser pulse with atomic cluster of Ar and their interpretation by the nano-plasma model, it was found that the atomic clusters as solid target after the collision with the laser pre-pulse become ionized and the plasma produced. Then due to heating and ionization mechanism the electron density increases. As well the laser energy is transferred to electrons and accelerate them. So with this interaction we can produce high energy electrons. As well with review the results of simulation it is clear that by increasing the laser intensity we can produce high energy and high density electrons. For full compliance all results with nano-plasma model excellence and flawless of this model confirmed again.

5. References

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