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COULOMB EXPLOSION OF Ar CLUSTERS
IRRADIATED BY AN INTENSE FEMTOSECOND LASER FIELD

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ABSTRACT: We study the rare gas clusters (Ar, Pb and K), containing 5.10^7 atoms per cluster, irradiated by an intense femtosecond laser pulse ($I_{pic} \approx 10^{18}$ W/cm^2). The irradiation of these clusters by the intense laser leads to high excitation energies which are the source of energetic electrons, electronics emission, highly charged and energetic ions and fragmentation processes.

For the study of different mechanisms of ionization of the cluster, we have used the nanoplasma model proposed first by T. Ditmire et al.[1] In this model, we consider a cluster with a radius of a few nanometers irradiated by a linearly polarized intense laser field. The dimensions of the cluster are much smaller than the laser wavelength ($\lambda \approx 400$ to 1000 nm). The model treats all ionization mechanisms: heating, electronic emission and the expansion process of the cluster. The goal of our study is to investigate in detail the expansion and explosion of the cluster and to study the different factors leading to the final explosion. We have found that the hydrodynamics pressure is larger than the coulomb one which is not the case in the previous work.

KEY-WORDS: intense laser, intense femtosecond laser applications, nano-materials, rare gas clusters, metallic clusters

1. Introduction

In recent years, much effort has gone into the understanding of interaction of short intense laser pulses with matter [1-3]. Analogous studies on clusters pioneered by McPherson et al [4], have appeared with a recent demonstration of deuterium fusion in clusters. Some discussion has been devoted to the question if the expansion of the cluster is driven by Hydrodynamics or by Coulomb pressures.

The investigation of the interaction of atomic clusters irradiated by intense laser field has received a great attention after the development of high peak power femtosecond lasers capable of producing focused light intensity exceeding 10^{17}w/cm²[5]. These high intensities have been used to study the production of highly charged ions from multiphoton ionization of individual atoms [6], and the optical ionization of small molecules, in which the resulting Coulomb explosion produces ions with kinetic energy of up to 2kev [7]. The irradiation of clusters by intense laser pulse may lead to: the emission of high energy (kev) electrons, highly charged and very energetic ions and fragments as well as x-ray production [8,9]. The basic mechanisms in laser cluster interaction are: the laser strips a sizable number of electrons from their parent atoms; these electrons form quasi free electrons. The global response of the cluster is characterized by a heating of the electron cloud and electronic emission. The net charge and the high excitation energy acquired by the cluster lead to its final explosion.

Several models have been developed to explain the experimental features observed in the interaction of high laser intensity with atomic clusters. In our work we use the nanoplasma model developed by T. Ditmire et al [1] and reformulated by M. Belkacem et al[2, 3]. the nanoplasma model offers a complete scenario of the interaction taking into account ionization, heating and explosion processes simultaneously. The cluster is treated as a spherical plasma where plasmon resonance takes place. In this model, large electron temperatures are reached and highly charged ions are produced at resonance. The electron gas exerts a strong hydrodynamics pressure which combined with the coulomb one, leads to the final explosion of the cluster.

In this paper we examine the interaction of intense femtosecond laser pulse with the large clusters (410^3- 510^7 atoms) using the nanoplasma model. We study the plasma near the plasmon resonance, we describe briefly the different processes of ionization of the nanoplasma, we present some results of this interaction and finally we draw our conclusion.

2. Nanoplasma model

In this model, we consider that the cluster has a radius of few nanometers in the electric field of an intense linearly polarized laser field,

$$E = E_0 \sin(wt) f(t) e_z \qquad (1)$$

Where E_o is the amplitude of the field, e_z direction of the polarization and f(t) is a time dependent wrapper (Gaussian wrapper). The dimensions of the cluster are much smaller than the laser wavelength. We assume that the electric field inside the cluster is uniform. The atoms produced ions can be ionized by several processes. First, the laser field ionizes cluster atoms through tunnel ionization. Once free, these electrons will ionize atoms or ions through collisions. Due to the high excitation and densities reached inside the cluster, the collisional process is found to be important and produces a higher charge state.

The field inside the cluster E_{int} is the sum of the incident field and the polarization field radiated by all charges in the cluster. Assuming the dipolar approximation, the field inside a dielectric sphere is uniform and reads,

$$E_{\text{int}} = \frac{3}{|\varepsilon + 2|} E_{ext} \qquad (2)$$

where E_{ext} is the amplitude of the external field and ε is the plasma dielectric constant. Within the drud model, we can write:

$$\varepsilon = 1 - \frac{\omega_p^2}{\omega(\omega + i\nu)} \qquad (3)$$

Where

$$\omega_p = \sqrt{\frac{ne^2}{\varepsilon_0 m}} \qquad (4)$$

is the electronic plasma frequency, n the electron density and ν the electron collision frequency.

3. Results and discussion

We consider a Ar cluster containing 510^7 atoms irradiated by a Gaussian laser pulse with wavelength 780nm, pulse duration 200fs, and peak intensity 10^{18}w/cm². The considered ionization mechanisms are direct optical ionization through tunnel ionization and electron-ion collisions. The variation of the radius of the cluster as a function pf time is shown in Figure1.

We show in figures 2 the external and internal electric fields as a function of time; by field ionization electrons are produced from the neutral atoms.

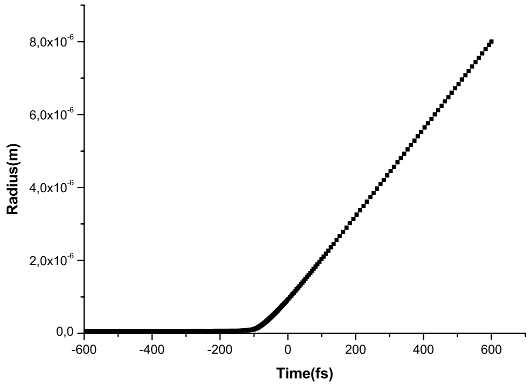

Figure 1: Variation of Ar cluster (510^7 atoms) radius subjected to 780nm laser pulse with peak intensity 10^{18} w/cm^2.

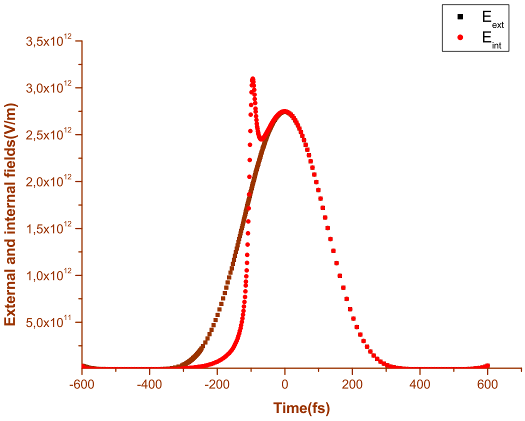

Figure 2: Variation of the external and internal fields as a function of time for a 510^7 atoms Ar cluster.

Time t=0 is the time at which the laser reaches the cluster at maximum intensity, the formation of nanoplasma occurs when a sufficiently large number of electrons have been stripped from the atoms by tunnel ionization. Due to the small value of the electron-ion collision frequency at resonance, other damping phenomena become more relevant (electron collision with the surface). When electrons velocities increase, the electrons quickly reach the surface and my be reflected many time during the resonance duration.
The field inside the cluster is shielded for the value of electron densities $n_e > 6n_c$ where:

$$n_e = \frac{\varepsilon_0 m_e \omega}{e^2} \qquad (5)$$

and reaches a maximum when $n_e = 3n_c$. The electron density increases with time and the electron absorbs energy from the field through collisions. The energetic electrons can then escape from the cluster and the shielding disappears as the electron density n_e drops down to n_c. The electric field is then enhanced and reaches a maximum (figure2).
When the parent atoms are ionized, the electrons inside the cluster absorb the electromagnetic power, heating up the cluster through which electrons absorb photons when colliding with ions and we have a large ionization rate. During the rising edge of the pulse, electrons are produced from the neutral atoms by field ionization. The rapid increase of the number of quasi free electrons leads the system through a first resonance. In figure 3, we show the variation of the electron density normalized to the critical one as a function of time.
The electron density rises to reach $6n_c$; at this point more electrons are liberated through tunnel and optical ionization. When the electron density is higher than $3n_c$, the field inside the cluster is shielded from the external one. The combined effect of free steaming of electrons out of the cluster and the hydrodynamic expansion of the cluster is that the electron density starts to fall, after peaking at over $\approx 27n_c$ at time $t \approx -283.68$fs. The field in the cluster again starts to rise as the electron density drops. At $t \approx -97.07$fs the electron density in the cluster

drops to $3n_c$ and we have the resonance of the internal field (with the higher value 3.11 10^{12} V/m). The increase of the total charge of the cluster leads to increase of the coulomb pressure to 8.04 10^{12} bar (figure4). However, this value is small compared to the hydrodynamic pressure due to the hot electrons of $P_h \approx 6.06\ 10^{13}$bar. Those pressures cause a sharp increase in the cluster expansion (figure1), then the explosion of the cluster.

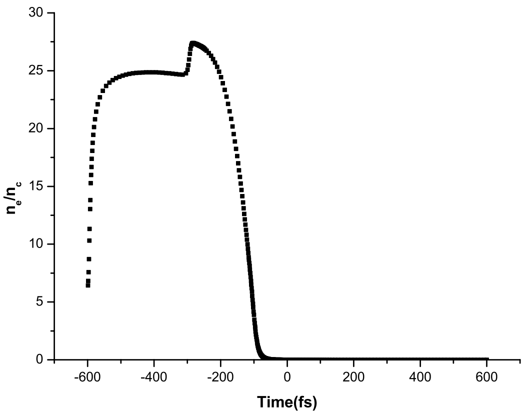

Figure 3: Variation of the electron density normalized to critical one as a function of time of Ar cluster (510^7 atoms).

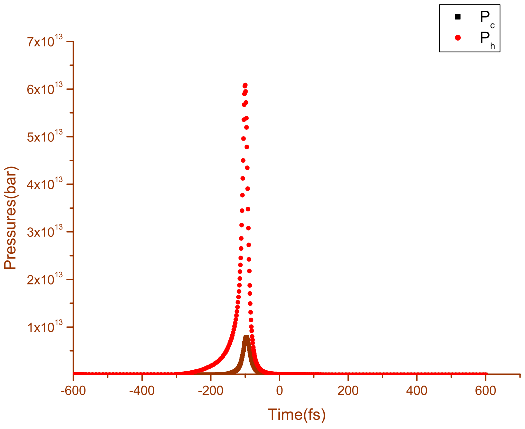

Figure 4: Variation of the Coulomb and hydrodynamic pressures as a function of time of Ar cluster (510^7 atoms).

The electron density drops rapidly due to both electron ionization and cluster expansion and the inner electric field becomes identical to the external one.

4. Conclusion

We have studied in this paper the dynamics of large clusters irradiated by intense and short laser pulses within the nanoplasma model. We have found that the atomic clusters are very efficient at absorbing laser energy, with the coupling of the laser energy into the cluster being predominantly by collisional heating of electrons. Large heating within the cluster results in rapid production of high ion charge states.

We have also shown that the rare gas clusters irradiated by an intense ($I_{pic}=10^{17}W/cm^2$) femtosecond laser pulse can produce a rapid heating of cluster by different process of collisions, and the cluster expansion also produce a very energetic electrons and ions which leads to the emission of the energetic electrons.

The internal field differs from the external one by the polarization effect of the nanoplasma. At resonance, the internal field is amplified, large electron temperatures are reached and highly charge ions are produced. The hydrodynamics pressure is larger than the Coulomb one which leads to the final explosion of the cluster.

5. References

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