Coulomb explosion of Ar_n clusters irradiated by intense femtosecond laser fields

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We study the dynamics of rare gas clusters (Ar_n), where $n \approx 10^6$ atoms per cluster, irradiated by an intense femtosecond laser pulse. The irradiation of these clusters by the intense laser leads to highly excitation energy which is the source of energetic electrons, electronic emissions, highly charge and energetic ions and fragmentation process. For the study of different mechanisms of ionization of the cluster, we are used the modified nanoplasma model. We have investigated in detail, the dynamics of expansion and explosion of the cluster by varying the pulse duration at constant laser intensity, and have studied the different factor leading to the final explosion of the cluster.

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1. Introduction

Interactions between intense ultra short high laser fields and clusters have received a great attention over the last few years [1-7]. The highly efficient coupling of the laser energy allows extremely large absorption rates of nearly 100% [8]. Cluster irradiation may thus lead to exceptionally large energy deposits which produce at once a hot and dense plasma state inside the irradiated species [9]. This laser cluster interaction may be the source of high energy (keV) electrons [3], highly charged and very energetic ions [2] or fragmentation process [4] as well as X rays in the keV range [10-13].These high intensities have been used to study the production of highly charged ions from multiphoton ionization of individual atoms, and the optical ionization of small molecules, in which the resulting Coulomb explosion produces ions with kinetic energy of up to 2kev [14-16]. 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 and others [17,18]; we have modified and adapted the model to our study. The goal of our study is to investigate in detail the dynamics of expansion and explosion of the cluster and to study the different factor leading to the final explosion.

In this paper we examine the interaction of intense femtosecond laser pulse with large Ar_n clusters ($n \approx 10^6$ atoms) using the modified nanoplasma model with the inclusion of the term of electron surface collisions in the expression of the electron ion collision frequency. We describe briefly the nanoplasma model and the expansion process of the cluster, we present some results of this study and finally we draw our conclusion.

2. Nanoplasma model

The first phenomenological attempts to understand the ionization dynamics of clusters was the nanoplasma model proposed firstly by T. Ditmire et al [17]. The nanoplasma model offers a complete scenario of the interaction taking into account ionization, heating and explosion processes simultaneously. The cluster is treated as spherical nanoplasma 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 [6].

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 given by,

$$\vec{E} = E_0 \sin(wt) f(t) \vec{e_z} \tag{1}$$

Where $\boldsymbol{E_0}$ is the amplitude of the field, $\vec{\boldsymbol{e_z}}$ direction of the polarization and f(t) is a time dependent envelope (Gaussian envelope). 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.

In the standard version of the nanoplasma model, the electrons collide only with ions in the plasma. The electron-ion collision frequency can be described by the standard Coulomb formulas of Silin [19]. These frequencies have analytic formulas for the extreme cases in which $v_q << v_{th}$ and $v_q >> v_{th}$. For our calculation, we consider not only collisions of electrons with individual ions, like the standard model, but also collisions with surface of the cluster. Therefore, we use the expression of the total electron-ion collision frequency given by

$$\nu(w) = \nu_{ei}(w) + \nu_s(w) \tag{2}$$

Where ν(w) is the total electron-ion collision frequency; knowing the electric field inside the cluster, the various processes occur on the time scale of the laser pulse such as ionization, energy absorption and cluster expansion. ν_{ei} is the electron ion collision frequency of the standard model and ν_s is the electron-surface collision frequency added in our model and given by

$$\upsilon_s = \frac{v}{R} \tag{3}$$

Where R is the radius of the cluster and v is the effective electron velocity

$$v = \sqrt{v_{th}^2 + v_q^2} \tag{4}$$

With thermal velocity

$$v_{th} = \sqrt{\frac{k_B T_e}{m}} \tag{5}$$

And quiver velocity of the electron in the field defined given by

$$v_q = \frac{eE_{\text{int}}}{mw} \tag{6}$$

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 given by,

$$E_{\text{int}} = \frac{3}{|\varepsilon + 2|} E_{ext} \tag{7}$$

where E_0 is the amplitude of the external field and ε is the dielectric constant. Within the drud model, we can write:

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

w_p is the electronic plasma frequency, ν is the total electron-ion collision frequency.

2.1. Cluster expansion

Tere are two expansion scenarios for heated clusters. The ponderomotive potential of the laser is large enough to remove all the electrons out of the cluster, a coulomb explosion is going to occur. A hydrodynamic expansion is excepted if the electrons stay under the influence of the electrostatic cluster field.

After formation of the nanoplasma, the cluster expands during and after the laser pulse due to the pressure of the hot electrons and a charge buildup in the cluster. Heating the nanoplasma, via inverse bremsstrahlung, then production of electrons with ionization processes leads to the increase of the electron pressure; thus the nanoplasma will expand. This expansion is governed by the following equation [20]:

$$\frac{d^2R}{dt^2} = 5\frac{P_t}{n_i m_i}\cdot\frac{1}{R} \tag{9}$$

Where

$$P_t = P_c + P_h \tag{10}$$

P_c, P_h are the coulomb and the hydrodynamic pressures, and R denotes the nanoplasma radius.

3. Results and discussion

We consider a Ar_n cluster containing 510^5 atoms irradiated by a Gaussian laser pulse with wavelength 800 nm, pulse duration 200 fs, and peak intensity 10^{21} W/m². The considered ionization mechanisms are direct optical ionization through tunnel ionization and electron-ion collisions. The temporal evolution of the cluster radius is shown in figure 1. In the beginning, the cluster expands rapidly during the pulse when heating of the electrons in the cluster begun; after that, the radius values tend to very high values which characterize the final explosion of the cluster. The contributions of the hydrodynamic and coulomb pressures are shown in figure 2. During the majority of the plasma expansion dynamics seen in figure 1, the dominant pressure is the hydrodynamic pressure with a little contribution from the coulomb pressure. The increase of the total charge of the cluster leads to the increase of the coulomb pressure to 3,53 10^{11} Bar (Fig. 2). However, this value is small compared to the hydrodynamic pressure due to the hot electrons, $P_{hmax}\approx 2{,}84\ 10^{12}$ Bar. Those pressures cause a sharp increase in the cluster expansion (Fig. 1), then the explosion of the cluster.

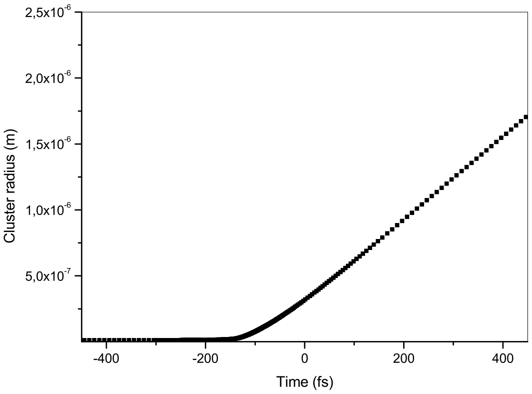

Fig. 1. Variation of Ar_n (n=5 10^5 atoms) cluster radius R as a function of time irradiated with 200 fs, 800 nm laser pulse and peak intensity of 10^{21} W/m^2.

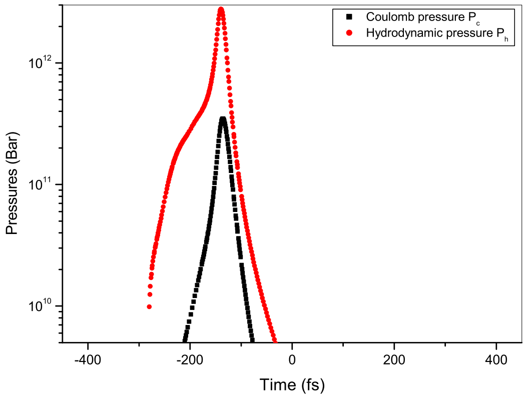

Fig. 2. Temporal evolution of the coulomb and hydrodynamic pressures of Ar_n (n=5 10^5 atoms) cluster (FWHM= 200 fs, λ=800 nm and I=10^{21} W/m^2).

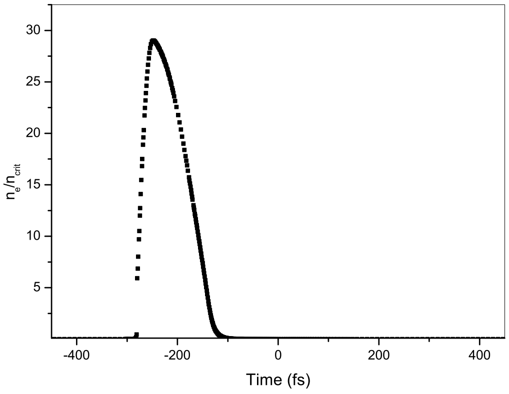

Fig. 3. Temporal variation of the electron density normalized to the critical one of Ar_n (n=5 10^5 atoms) cluster, I= 10^{21} W/m^2, 200 fs (FWHM) and λ = 800 nm.

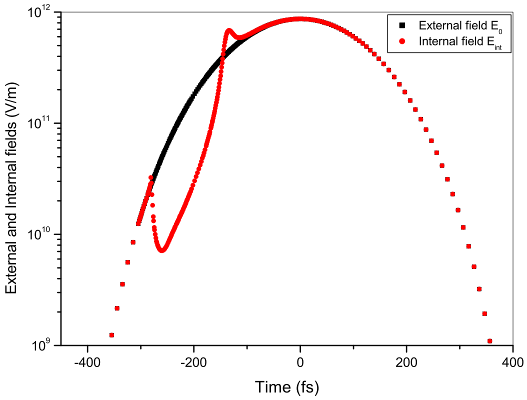

Fig. 4. Variation of the external and internal fields as a function of time for Ar_n cluster (n=5 10^5 atoms, Full width at half maximum (FWHM) =200fs, λ=800 nm and I=10^{21} W/m^2).

We show in figure 3 the variation of the electron density normalized to the critical one with the term of electron-surface collisions as a function of time. 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 may be reflected many times during the resonance duration. The field inside the cluster (Fig. 4) is shielded for the value of electron densities $n_e > 3n_{crit}$, where n_{crit} (the critical electron density), and reaches a maximum value E_{max}= 3,29 10^{10} V/m when $n_e = 3n_{crit}$. The electron density increases with time and the electrons 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 $3n_{crit}$. The electric field is then enhanced again and reaches a maximum value E_{max}=7,12 10^{11} V/m.

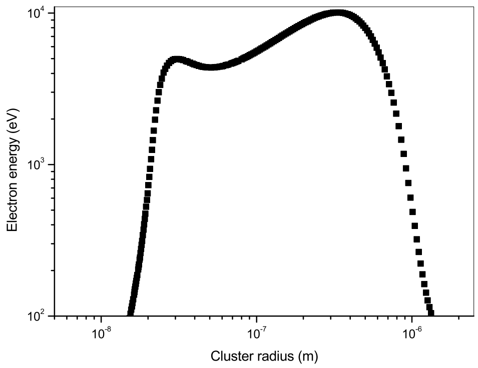

Fig. 5. Variation of electron energies with cluster radius for Ar_n (n=5 10^5 atoms) cluster irradiated with 200 fs, 800 nm laser pulse and peak intensity of 10^{21} W/m^2.

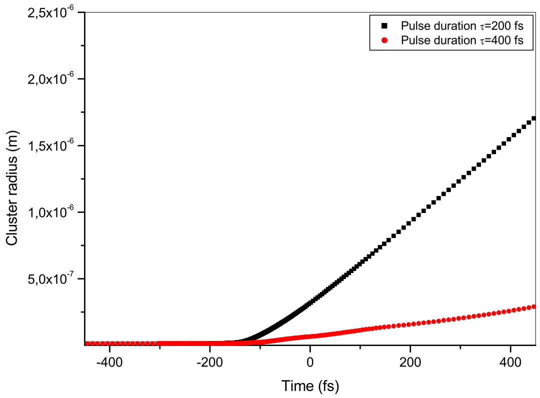

Fig. 6. Temporal variation of Ar_n *(n=5* 10^5 *atoms) cluster radius R with pulse duration (τ=200-400 fs) irradiated with 200 fs, 800 nm laser pulse and peak intensity of* 10^{21} W/m^2*.*

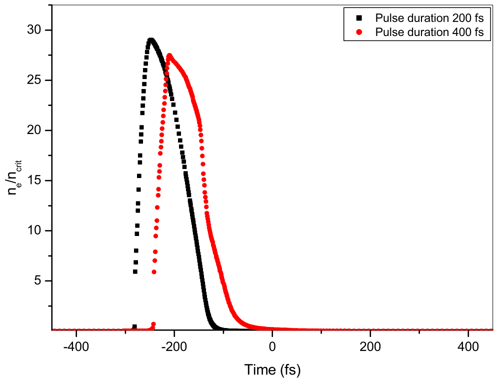

Fig. 7. Variation of the electron density normalized to the critical one with pulse duration (τ=200-400 fs) as a function of time for Ar_n *(n=5* 10^5 *atoms) , I=* 10^{21} W/m^2*, 200 fs (FWHM) and λ=800 nm.*

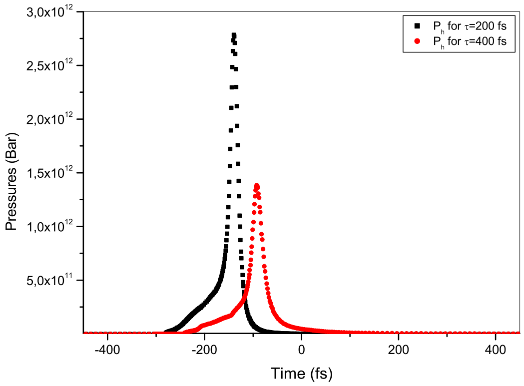

Fig. 8. Temporal variation of hydrodynamic pressure with pulse duration (τ=200-400 fs) for Ar_n *(n=5* 10^5 *atoms) clusters, laser parameters are the same as in figure 6.*

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; the electron density (Fig. 3) rises to reach $3n_{crit}$ at time t=-280,68 fs. When the electron density is higher than $3n_{crit}$, the field inside the cluster is shielded from the external one (see Fig.4). 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 $\approx 29n_{crit}$ at time t≈-248,04 fs. The field inside the cluster again starts to rise as the electron density drops. At t≈-136,66 fs, the electron density in the cluster drops to $3n_{crit}$ and we have the second resonance of the internal field (with higher value 7,12 10^{11} V/m), The electron density drops rapidly due to both electron ionization and cluster expansion and the inner electric field becomes identical to the external one. The electron energy as a function of cluster radius is shown in Figure 5 for the pulse duration 200fs, 5 10^5 atoms Ar cluster and pulse intensity 10^{21} W/m^2. The maximum electron energy is about 5,27 keV at the time of explosion of the cluster, and about 10,58 keV after the final explosion of the cluster. The electron surface collision frequency added in our model has an important influence on the dynamics of the nanoplasma.

3.1 Influence of the laser pulse duration

In the following, we are interesting to investigate the dependence of the cluster radius, electron density and hydrodynamic pressure on the laser pulse duration with the same intensity. The temporal evolution of the cluster radius as a function of time is shown in Figure 6, we see that we have a rapid expansion and explosion in the case of pulse duration 200fs than 400fs. The electron density normalized to the critical one is shown in Figure 7. The times of resonance are different; n_e reach the value $3n_{crit}$ at time t=-280,68 fs for the case of 200 fs, but t=-242,92 fs for the case of pulse duration of 400 fs, and the times of the second resonance are also different, -136,66 fs and

-88,65 fs respectively. The electron density drops after peaking a maximum value of order of $29n_{crit}$ for the case of 200 fs larger than $27n_{crit}$ for the case of 400fs. Figure 8 show the variation of the hydrodynamic pressure as a function of time for Ar_n (n= 510^5) clusters irradiated with a laser pulse of 10^{17} W/cm^2. The maximum value of the hydrodynamic pressure is 2,78 10^{12} Bar in the case of 200 fs two times as big than for the case of 400 fs where $P_{hmax}=1{,}3910^{12}$ Bar.

4. Conclusions

The interaction of intense laser fields with cluster targets of Ar_n produced hot and energetic electrons. 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. We have found electrons with energies up to 10 keV, two resonances at different times when adding the electron-surface collision frequency term for the two cases of 200 fs and 400 fs, the cluster expands and explode rapidly, the hydrodynamic pressure for the case of 200 fs is two times as big than for the case of 400 fs and the electron density drops after peaking a maximum value of order of $29n_{crit}$ and $27n_{crit}$ respectively. The hydrodynamic pressure is larger than the Coulomb one; therefore, the dynamics of expansion of the cluster is driven by the hydrodynamic pressure. Finally, the electron surface collision frequency added in our model has an important influence on the dynamics of the nanoplasma.

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