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Nanoplasma Formation From Atomic Clusters Irradiated by Intense Femtosecond Lasers

Boucerredj Noureddine and Khaled Beggas

Abstract

The nanoplasma formations of Na and Kr clusters, which contained 2×10^7 atoms per cluster, irradiated by intense femtosecond laser field have been predicted in detail within the framework of the modified nanoplasma model. Based on this modified model, ionization process, heating, expansion, and explosion of the cluster have been studied. When laser intensity is above a critical value, it blows off all of electrons from the cluster and forms a non-neutral ion cloud. The analytic calculation provides time evolution of radius of the cluster, internal and external fields, coulomb and hydrodynamic pressures, electron density, and ion and electron energy. During the coulomb explosion of the resulting highly ionized, high-temperature nanoplasma, ions acquire their energy. It is shown that ultrafast ions are produced in this comparative study (4.4 keV for Kr cluster and 2.2 keV for Na cluster), which can be the source of energetic ions. We have found that the coulomb pressure is little than the hydrodynamic pressure for both clusters.

Keywords: large clusters, nanoplasma, laser plasma interaction, laser-produced plasma, ion source, cluster explosion

1. Introduction

During the last years, nanoplasma (nanometer scale plasma) formed from atomic clusters irradiated by high-power femtosecond lasers, capable of achieving a light intensity up to 10^{21} – 10^{22} W/cm², has attracted a great attention and has been studied by several groups [1–5]. This large interest is due to the high energetic ions and electrons produced when rare gas clusters explode [5, 6]. The intense femtosecond laser field ionize atoms of the cluster several times and ions reaches a high degree of ionization [7–9], and are very effective to produce strong X-ray radiation [10]. In addition, fusion reaction has been observed in laser deuterium cluster interaction indicating that nuclear fusion occurs after explosion of the cluster [11]. The measurements of the energy absorption by the formed plasma have shown that the plasma absorbs a large fraction of the incident laser energy [12]. The interaction of rare gas and metallic clusters with ultrafast lasers has become a topic of great interest; a new fundamental insight into ultrafast laser-driven excitation and decay dynamics of many particle systems can be gained [13]. Macroscopic and hydrodynamic impact energy transfer from nanoplasma electrons to ions in exploding cluster using molecular dynamics simulation has been studied recently [14]. When

the laser interacts with clusters, it changes the regime of electromagnetic wave propagation, and very efficient absorption of radiation has been demonstrated with a formation of very high temperature under dense plasma [15, 16]. The coulomb explosion plays an important role in the case of small-diameter clusters [17].

The interaction of intense femtosecond laser field with atomic cluster leads to the ionization of the parent atoms of the cluster. Ionization of the cluster begins on the rising edge of the laser field. Parent atoms absorb laser intensity and liberate a small number of electrons by direct optical ionization which produces a gas of electrons that forms the nanoplasma. The collisional ionization becomes important between electrons and ions leading to the rapid heating of the cluster to a non-equilibrium superheated state then the expansion of the cluster [18, 19].

The interaction of single clusters with intense femtosecond laser produces the hot electrons with energy up to 3 keV [20, 21]. After heating up the cluster, charge separation of the hot electrons and the repulsive coulomb force between the positive ions leads to the explosion of the cluster, and ions acquire their energy by the conversion of the energy deposited by the laser in the cluster to ion kinetic energy.

In this present research, we study the formation of the nanoscale plasma from the irradiated clusters by an intense femtosecond laser field, and we investigate a comparative behavior of the different physical parameters of the formed nanoplasma from rare gas (Kr) and metallic (Na) clusters within the framework of the modified nanoplasma model. After a general introduction on intense laser cluster interaction and plasma formation, we show in Section 2 a brief description of the nanoplasma model, followed by a discussion of the obtained results in Section 3. Finally, we report the obtained results in the conclusion section.

2. Nanoplasma model

The development of the numerical model called nanoplasma model was made firstly by Ditmire et al. [9], and after that reformulated by Megi et al. [18] by the addition of the term of electron collisions with surface in the expression of the electron-ion collision frequency. This numerical model has proved its success in reproducing experimental results of the interaction of single cluster with intense femtosecond laser field [19] and describes the interaction in terms of the formation of high-density nanoplasma.

In this model, the expanding cluster was treated as a spherical nanoplasma, subjected to the intense laser field. Ionization process such as field ionization is described by the Ammosov, Delone, and Krainov model [22]. Tunnel and collisional ionization are described using the Lotz formula [23]. Collisional ionization in the nanoplasma leads to the production of highly charged ions.

2.1 Ionization mechanisms

The basic mechanisms in this model are that, the laser strips electrons from the parent atoms by direct optical ionization and collisional ionization. The direct optical ionization begins when laser pulse liberates a small number of electrons. Field ionization is described in this model by Ammosov et al. [18, 22, 24], and collisional ionization, which occurs from inelastic collisions between electrons and ions, is described by the Lotz formula [9, 18, 23]. Due to the high excitation and hot electrons and densities reached inside the cluster, collisional ionization is the dominant ionization mechanism in the nanoplasma leading to the production of highly charged ions. The laser deposits its energy into the free electrons inside the cluster. These electrons absorb the magnetic power and heating up the ions. The heating in

the cluster occurs through inverse bremsstrahlung collisions. The density of the energy deposition $\frac{\partial u}{\partial t}$ in the cluster is given by [9, 25]:

$$\frac{\partial u}{\partial t} = \varepsilon E_{\text{int}} \frac{\partial E_{\text{int}}}{\partial t} \quad (1)$$

where ε is the plasma dielectric constant.

In this model there are three main assumptions: First, we assume that $\lambda \gg R_0$, where λ and R_0 are the laser wavelength and the initial cluster radius, respectively. Second, the electronic and ionic densities are distributed uniformly within the cluster. The third assumption is that the electrons are assumed to be instantaneously thermalized and their energy distribution is Maxwellian. The nanoplasma model takes into account the highly efficient collisional heating which is calculated in this model as the heating of a uniform dielectric sphere under the electric field of the laser. The internal electric field is given by [26].

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

where E_{ext} is the external electric field, t is the time, and ε is the plasma dielectric constant given by a Drude model,

$$\varepsilon = 1 - \frac{w_p^2}{w(w + i\nu)}, \quad (3)$$

where w is the plasma frequency, ν is the total electron-ion collision frequency, and w_p is the electronic plasma frequency given by

$$w_p = \sqrt{\frac{n_e e^2}{\varepsilon_0 m}}, \quad (4)$$

where n_e is the electron density, ε_0 is the vacuum dielectric constant, e is the electron charge, and m is the electron mass.

The external electric field is given by

$$\begin{aligned} \vec{E}_{\text{ext}}(t) &= E_0 \sin(\omega t) f(t) \vec{e}_z, \\ \vec{E}_{\text{ext}}(t) &= E_0 \exp\left(-2 \ln 2 \left(\frac{t}{\tau}\right)^2\right) \vec{e}_z, \end{aligned}$$

where τ is the laser pulse duration at the full width at half maximum (FWHM), $f(t)$ is a Gaussian distribution of laser profile, and E_0 is the amplitude of the laser field given as the maximum laser field, $E_{\text{max}} = \sqrt{\frac{2I_{\text{max}}}{\varepsilon_0 c}}$, where c is the light velocity.

The total electron-ion collision frequency including the electron-surface collision frequency, $\nu_s = v/R$, is given by the formula

$$\nu = \nu_{ei} + \nu_s = \nu_{ei} + \frac{v}{R}, \quad (5)$$

where v is the velocity of the electrons, R is the cluster radius, and ν_{ei} is the electron-ion collision frequency given by [27, 28]

$$\nu_{ei} = \frac{n_i \langle Z^2 \rangle e^4 \ln \Lambda_1}{2(\pi \varepsilon_0 m_e)^2 v^3}, \quad (6)$$

$$v = \sqrt{v_{th}^2 + v_{osc}^2}, \quad (7)$$

where $v_{th} = \sqrt{k_B T_e / m}$ is the thermal velocity and $v_{osc} = \frac{e E_{int}}{m_e \omega}$ is the oscillation velocity of the electron in the field, $\langle Z \rangle$ is the mean ion charge, and $\ln \Lambda_1$ is the modified coulomb logarithm given by the expression.

$$\ln \Lambda_1 = \begin{cases} \frac{1}{4} \ln^2 \left(\frac{1 + m_e v_{osc}^2}{\hbar \omega} \right), & \text{for } \hbar \omega \gg k_B T_e \\ \frac{1}{4} \ln^2 \left(1 + \frac{v_{osc}^2}{v_{th}^2} \right) + \ln \left(\frac{v_{osc}^2}{v_{th}^2} + \exp \left(\frac{1}{3} \sqrt{\frac{\pi}{2}} \right) \right) \ln \Lambda, & \text{for } \hbar \omega \ll k_B T_e. \end{cases} \quad (8)$$

where k_B is the Boltzmann constant, T_e is the electron temperature (see [9] and [18]), and $\ln \Lambda$ is the classical coulomb logarithm [29].

2.2 Cluster expansion

The expansion of the nanoplasma is driven by two mechanisms. First, the hydrodynamic heating is driven by the hot electron pressure in the cluster. The heated electrons or the heated nanoplasma start to expand, then pull the heavy ions. The electron or hydrodynamic pressure has the expression

$$P_h = n_e k_B T_e, \quad (9)$$

where n_e is the electron density in the cluster $n_e = \frac{N_e}{\frac{4}{3}\pi R^3}$ and N_e is the number of electrons in the cluster.

Second, the coulomb explosion is driven by charge buildup on the cluster. After ionization, some hot electrons escape the coulomb barrier formed by ions, leaving a net positive charge on the cluster. The resulting repulsive coulomb force leads to the expansion of the cluster. The coulomb pressure is given by

$$P_{Coul} = \frac{3Q^2 e^2}{32\pi^2 \epsilon_0 R^4}, \quad (10)$$

where Q is the built-up charge on the cluster due to electron escape (see [9] and [18]). The total pressure is given by

$$P = P_h + P_{Coul} \quad (11)$$

The coulomb pressure scales as $(1/R^4)$ shows that it will be important for small clusters. The hydrodynamic pressure scales as $(1/R^3)$ is therefore more important for large clusters. Then, the cluster radius equation is given by

$$\frac{\partial^2 R}{\partial t^2} = 5 \frac{P}{n_i m_i R}, \quad (12)$$

where n_i and m_i are the density and mass of ions in the cluster, respectively.

The ion energies from cluster explosions are due to the electron-ion collisions heating up the electrons, but not the ions. This can be seen from the electron-ion equilibration time. In the other hand, there is insufficient time for electron energy to be transferred to the ions through collisions. Instead, the ions gain energy in the hydrodynamic expansion, where the thermal energy of the electrons is converted to

ion kinetic energy or through coulomb explosion. For a hydrodynamic expansion, the mean ion energy will be of order [24]

$$\langle E_{ion} \rangle \approx \langle Z \rangle k_B T_e, \quad (13)$$

where $\langle Z \rangle$ is the mean ion charge state. The coulomb explosion is the main process by which ions gain kinetic energy in the intense laser field.

The rate of the temperature decrease from the cluster expansion is given by [9]:

$$\left. \frac{\partial T_e}{\partial t} \right|_{\text{exp}} = -2 \frac{T_e}{R} \frac{\partial R}{\partial t} \quad (14)$$

2.3 Electron-ion thermalization

The transfer of thermal energy to the cloud ions in the cluster nanoplasma results from the coulomb collision of energetic electrons, which can be described by a thermal equilibration rate given by [9]

$$\left. \frac{\partial T_e}{\partial t} \right|_{eq} = - \frac{T_e - T_i}{\tau_{eq}} \quad (15)$$

The electron-ion equilibration time τ_{eq} is given by [9, 30]

$$\tau_{eq} = \frac{3m_e m_i}{8\sqrt{2\pi} n_i z^2 e^4 \ln \Lambda} \left(\frac{k_B T_e}{m_e} + \frac{k_B T_i}{m_i} \right)^{\frac{3}{2}} \quad (16)$$

where T_e is the electron temperature, T_i ion temperature, and m_e and m_i are the electron and ion mass, respectively.

3. Results and discussion

The calculation was carried out with an intense femtosecond laser including a peak intensity of 10^{17} W/cm², wave length of 390 nm, and pulse duration of

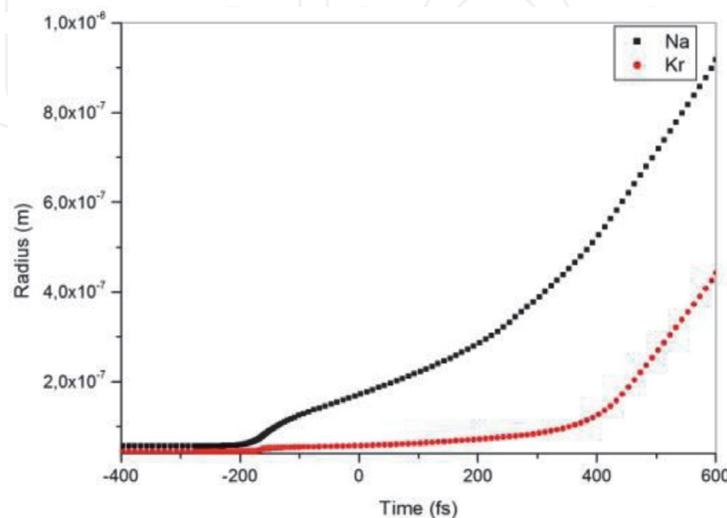


Figure 1. Calculated time evolution of the cluster radius R of the Na and Kr clusters contained 2×10^7 atoms in cluster irradiated by an intense femtosecond laser with a pulse duration of 200 fs (FWHM), wavelength of 390 nm, and peak intensity of 10^{17} W/cm².

$\tau = 200$ fs (full width at half maximum (FWHM)) irradiating the Kr and Na clusters containing 2×10^7 atoms per cluster. Inside the cluster, the temperature, the density gradient, and the internal field are assumed to be uniform. We have used the modified nanoplasma model to study the temporal variation of the different physical parameters (radius, electron temperature, expansion velocity, electron density, coulomb and hydrodynamic pressures, ion and electron energy, etc.) of the formed nanoplasma.

Time dependence of the cluster radius R for the rare gas Kr and metallic Na clusters is illustrated in **Figure 1**. Time evolution shows clearly a rapid expansion of the metallic cluster (Na) than the rare gas cluster (Kr). In the case of the metallic cluster, it expands rapidly due to the rapid ionization of the cluster.

The time zero in the calculation is the peak intensity of the laser at around -255 fs for Na cluster and -230 fs for Kr cluster; a small number of electrons are created through optical ionization; these electrons form the nanoplasma. The inelastic collisions between electrons and ions increase the number of electrons and ions. When electron density rises to reach $3n_{crit}$, where n_{crit} is the critical electron density given by the formula

$$n_{crit} = \frac{\epsilon_0 m_e \omega^2}{e^2}, \quad (17)$$

where ϵ_0 is the vacuum permittivity and ω is the laser frequency.

The internal field is amplified and becomes greater than the external one (**Figure 2**), and we have a strong absorption of the laser energy by the cluster. The first resonance (between laser field and the formed nanoplasma) occurs at $t \approx -250$ fs, in the Na cluster, but at -230 fs it occurs in Kr cluster (**Figure 3**); the cluster expansion velocity increases dramatically; and more electrons are liberated through tunnel, laser-driven, and thermal ionization. The hot electrons can leave the cluster to the $3n_{crit}$ resonance.

When the electron density n_e is greater than $3n_{crit}$, the field inside the cluster is smaller than the external one. The maximum value of the ration $\frac{n_e}{n_{crit}}$ is about 3.5 for Na cluster than 7 for Kr cluster; this difference in the time of resonances and the maximum values of the ratio $\frac{n_e}{n_{crit}}$ is caused by the number of electrons in such cluster. When the hot electrons leave the cluster and the cluster expands, the electron density starts to decrease at time -176 fs for Na cluster and -163 fs for Kr

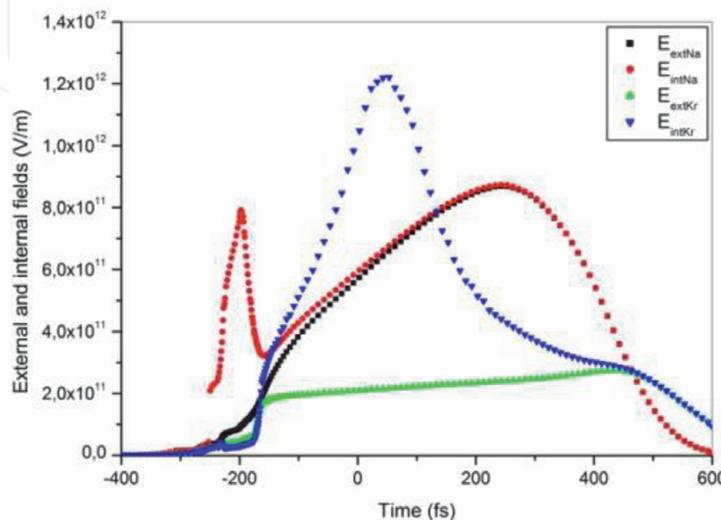


Figure 2.

Time dependence of the internal and external electric fields for the Na and Kr clusters contained 2×10^7 atoms per cluster. Same parameters of the laser are used as those in **Figure 2**.

cluster; the expansion of the cluster lowers the electron density to bring the system into resonance with laser field. The electron density in the cluster drops to $3n_{crit}$ (Figure 3), and we have the second resonance; (when the ratio $n_e/n_{crit} = 3$), at -200 fs and 47 fs for both clusters Na and Kr respectively. We see that times of resonances are different for both clusters, metallic cluster (Na) and rare gas cluster (Kr).

The field inside the cluster is strongly enhanced and reached the values 1.22×10^{12} V/m and 8.00×10^{11} V/m for Kr and Na clusters, respectively (Figure 2); then we have a very rapid deposition of the energy into the electrons; at this point, the ions very rapidly stripped the hot electrons. The internal field $E_{int}(t)$ is almost equal to the external field when the electron density n_e is very low.

The calculated time evolutions of the hydrodynamic pressure and the coulomb one are shown in Figure 4 for both clusters. The total charge on the cluster increases, and the repulsive forces lead to the increase of the coulomb pressure to

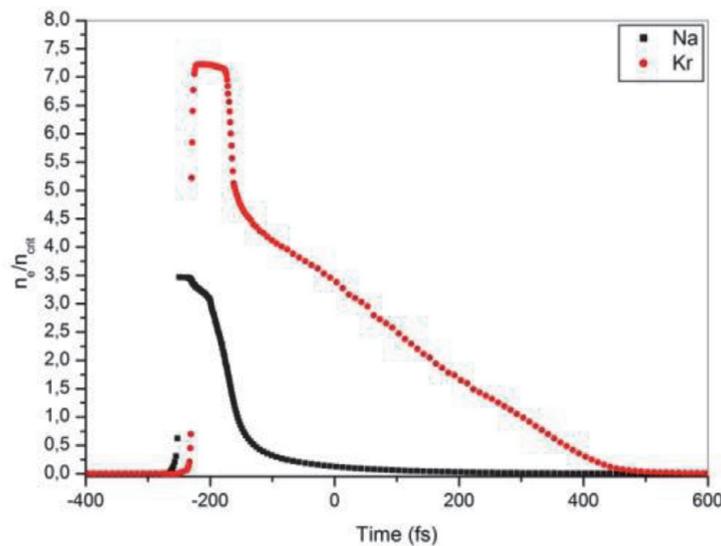


Figure 3. Calculated electron density n_e , normalized by the critical electron density n_{crit} as a function of time for 2×10^7 atoms Na and Kr clusters irradiated by an intense femtosecond laser with a pulse duration of 200 fs, wavelength of 390 nm, and peak intensity of 10^{17} W/cm².

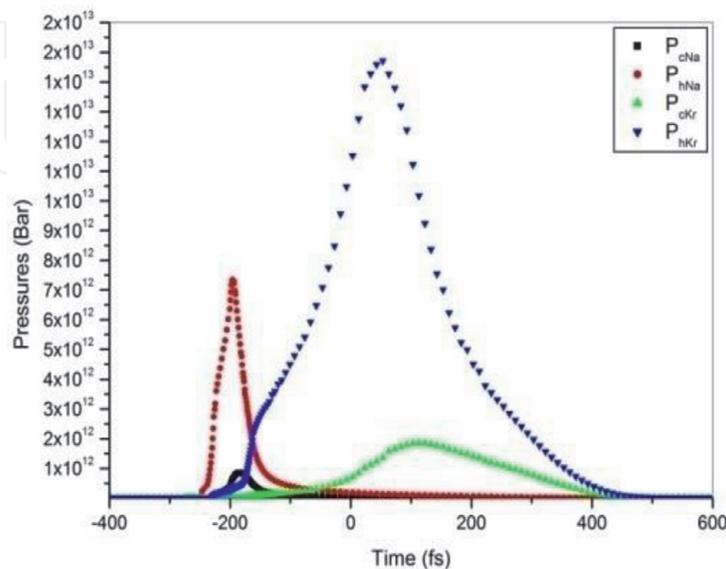


Figure 4. Calculated time variation of the coulomb and hydrodynamic pressures for Na and Kr clusters (contained 2×10^7 atoms) irradiated by an intense femtosecond laser with a pulse duration of 200 fs (FWHM), wavelength of 390 nm, and a peak intensity of 10^{17} W/cm².

2.0×10^{12} Bar and 9.9×10^{11} Bar for Kr and Na clusters, respectively. The values of the coulomb pressure for both clusters are small compared to the hydrodynamic pressure due to the hot electrons which are 1.5×10^{13} Bar for Kr cluster and 7.5×10^{12} Bar for Na clusters. This pressure leads to the increase of the cluster expansion velocity. During the majority of time, the dominant pressure is the hydrodynamic pressure with a little contribution of the coulomb explosion force; then the hydrodynamic pressure is dominant in driving the explosion. It has been noticed that for small diameter clusters, the coulomb explosion force plays a key role [5]. Our study of the coulomb explosion of large Kr and Na clusters shows that the hydrodynamic pressure plays an important role than the coulomb one like the previous experimental results [28].

When electrons gain energy through inverse Bremsstrahlung collisions, the time evolution of ion energy (Figure 5) roughly follows the evolution of the internal field. The increase of the electronic temperature leads to higher ionized states, and electron-free streaming rate increases sharply; then electrons with high energy can leave the cluster (Figure 6), as the maximum electron energy is above 3 and 6 keV for Na and Kr clusters, respectively.

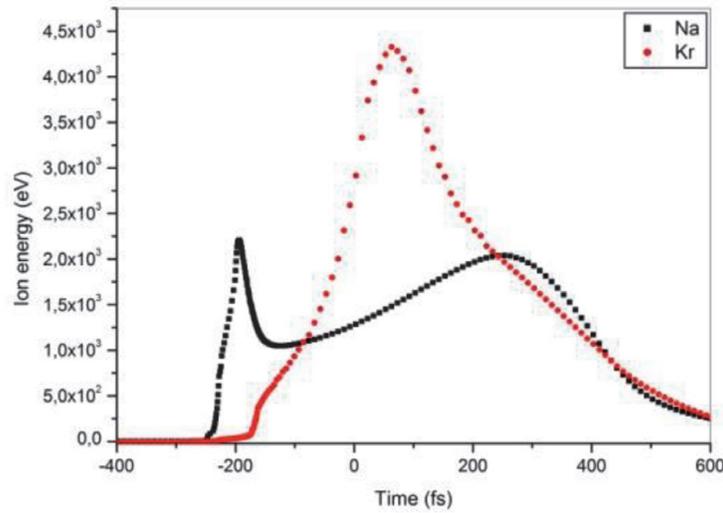


Figure 5.

Time evolution of ion energy for Na and Kr clusters. The laser parameters are the same as in Figure 4.

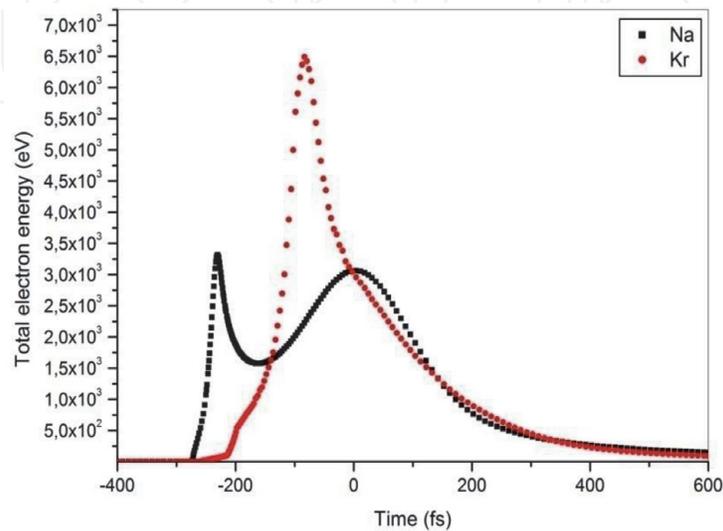


Figure 6.

Total electron energy as a function of time of Na and Kr clusters (contained 2×10^7 atoms) irradiated by a femtosecond laser with a peak intensity of 10^{17} W/cm², pulse duration of 200 fs, and wavelength of 390 nm.

The coulomb pressure induced by this loss of the plasma neutrality combined with the hydrodynamic pressure leads to the expansion of the nanoplasma. The enhancement of the internal field (**Figure 2**) leads to a very efficient absorption of the laser energy, resulting to the production of high charge states and high energetic ions 4.4 keV for Kr cluster and 2.2 keV for Na cluster (**Figure 5**). Then the combined effect of free streaming and the coulomb and hydrodynamic pressures leads to the final explosion of the cluster.

4. Conclusions

A modified nanoplasma model has been contributed to examine the cluster explosion dynamics and scaling of ion energies. We found that the excitation of large atomic cluster produces a superheated plasma. We also compared the behavior of the nanoplasma in the Kr rare gas and Na metallic clusters irradiated by an intense femtosecond laser. A similar behavior was found for both cases metallic and rare gas clusters in the time evolution of the different physical parameters (the cluster radius, the electron density, the internal and external electric fields, the pressures, and ion energies). The formation of nanoplasma in the case of Na cluster is rapid than in the case of Kr cluster –255 fs for Na cluster and –230 fs for Kr cluster. We have found that the ion energies in the Kr and Na clusters are 4.4 and 2.2 keV, respectively, which may provide a new ultrahigh energy ion source. The ionization and expansion of the Na metallic cluster are faster than that of the Kr rare gas cluster. The hydrodynamic pressure plays an important role in the interaction with the laser field for both cases (metallic and rare gas clusters); the hydrodynamic pressure was found of order of 10 times than the coulomb pressure; then we conclude that the hydrodynamic pressure is responsible for the dynamic of ionization, expansion, and explosion of the clusters.

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