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VACUUM HEATING OF LARGE ATOMIC CLUSTERS BY A SUPER-INTENSE FEMTOSECOND LASER PULSE

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The analytic approach of vacuum (Brunel) heating mechanism is generalized to the case of large atomic clusters irradiated by a super-intense femtosecond laser pulse. The hydrodynamic cluster expansion is taken into account in this approach. Simple universal expressions are obtained for the absorbed laser energy by a cluster and for the radius of an expanding cluster. The absorption of laser energy and the cluster expansion are determined by only one dimensionless field parameter.

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1. INTRODUCTION

Rapid developments in intense ultrashort laser technology have opened a new regime of laser–cluster interaction, in which intense laser pulses deposit their energy into solid targets faster than the hydrodynamic expansion of the cluster surface occurs. Hot electrons in laser–cluster plasmas can be generated by different absorption or acceleration mechanisms under different experimental conditions. At low laser intensities, inverse bremsstrahlung is the main absorption mechanism, which depends on the electrical conductivity associated with electron mean free path comparable to the interatomic spacing inside the cluster [1]. This absorption strongly decreases as the laser intensity increases.

Brunel [2] proposed that high-intense p-polarized laser pulses incident obliquely on an atomically abrupt metal surface could be strongly absorbed by pulling electrons into vacuum during an optical cycle and then returning them to the surface with approximately the quiver velocity. This is the so-called vacuum heating process.

Recently, hot electron generation was studied at high intensities [3]. Hot electron spectra and X-ray spectra from the bremsstrahlung radiation, when hot electrons undergo deceleration in solid targets, showed that when smooth solid targets were irradiated obliquely by p-polarized laser pulses, a group of hot electrons could be heated to a relatively low Maxwellian temperature. Another group of hot electrons with higher energies could be produced by nonlinear resonant absorption if there was a thin layer of preplasma in front of the target surface. Electrons produced by the inverse bremsstrahlung absorption process are known as thermal electrons and have energies less than 1 keV at modest laser intensities. The electrons generated by resonance absorption and the other nonlinear resonant absorption are called hot electrons, and have much higher kinetic energies. The energy absorption and the hot electron generation in the interaction of p-polarized femtosecond laser pulses with Aluminum solid targets have been studied. The laser delivered 150 fs pulses and produced a peak irradiance of $8 \cdot 10^{15}$ W/cm^2 at the focus. The measurements suggest that vacuum heating is the main heating mechanism for hot electrons with high energies.

It is clearly seen from other experimental data [4] that in the case of irradiation of solid targets by a p-polarized laser, the outgoing electrons are extracted from the critical surface by the Brunel absorption once in the laser oscillating period because the electron bunch length is almost equal to the laser wavelength. The laser wavelength and the intensity were 1 μm and $2 \cdot 10^{18}$ W/cm^2, respectively, in these experiments.

The third heating mechanism is the elastic reflections of inner electrons from the cluster surface [5, 6]. The absorption of laser energy is equal to $F_{in}^2/2\omega^2$ at

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each collision in the presence of laser field (analogously to the induced inverse bremsstrahlung at the collision of an electron with an atomic ion). Here, F_{in} is the electric field strength inside the cluster. The system of units $m_e = e = 1$ is used throughout the paper. Then the average collision rate ν is determined from the electron motion inside the cluster:

$$\nu \sim V_e/R.$$

Here, V_e is the electron thermal, or quiver, velocity inside the cluster. This mechanism is effective only near the Mie resonance when the Mie frequency

$$\omega_{Mie} = \omega_p/\sqrt{3}$$

is equal to the laser frequency ω during the cluster expansion. Then F_{in} can be larger than the external laser field strength F, resulting in large values of V_e. Far from the Mie resonance, we obtain

$$F_{in} \approx -\left(\frac{\omega}{\omega_{Mie}}\right)^2 F \ll F.$$

We see that the collision rate ν decreases as the cluster size R increases.

Inverse induced bremsstrahlung and vacuum heating are very different heating mechanisms. Electron heating at the inverse induced bremsstrahlung is proportional to the duration of the laser pulse. An electron acquires twice the oscillation field energy at each collision with an atomic ion; but inside the cluster, the electric laser field is much less compared to the external laser field, because the electron density in the cluster is higher than the critical density. The acquired electron energy at each collision is therefore small, but large absorption in experiments occurs due to large duration of a laser pulse at the leading edge of this pulse. At the trailing part of the laser pulse, the electron plasma becomes subcritical, and the external laser field freely penetrates the entire cluster. The doubled oscillation energy becomes large, but the cluster begins to expand so quickly that the rate of electron–ion collisions becomes very small, and there is no electron heating at the trailing edge. If now the duration of laser pulse is only 50 fs, then there is no time for many electron–ion collisions. Oppositely, the vacuum heating mechanism operates only with the external laser field, because an electron is ejected from the cluster, is heated by the external laser field, and returns to the cluster (where the internal laser field is negligibly small). Therefore, even a small number of electron ejections during the leading part of the femtosecond laser pulse results in large electron heating.

It follows from [7] that for clusters with radii larger than 10 nm, only a small amount of electrons leave the cluster, i.e., the Coulomb explosion mechanism is not realized, and hydrodynamic pressure of the free electron gas inside the cluster is the dominating mechanism for cluster expansion. The second requirement for fulfillment of the hydrodynamic approximation is that the laser pulse duration is large compared to the time between the neighboring electron–electron collisions. In the opposite case, a particle-in-cell description is required. This means in practice that the laser intensity should be a nonrelativistic quantity, because relativistic electrons practically do not collide with each other (and with atomic ions) during a femtosecond laser pulse.

In this paper, we report a theoretical study on hot electron generation in the interaction of superintense femtosecond laser pulses with large atomic clusters. The vacuum (Brunel) mechanism is generalized to the case of large atomic clusters with the hydrodynamic cluster expansion during the laser pulse taken into account. Femtosecond laser pulses are needed for experiments with clusters in order to prevent fast cluster decay before the peak of the laser pulse. A simplified version of the vacuum heating of electrons for deuterium clusters was considered in [8]. However, this approach did not take the screening effects at the electron ejection into account. Besides, the acquired electron kinetic energy was estimated only qualitatively. Finally, cluster expansion and multiple inner ionization of atomic ions were not considered in [8].

2. VACUUM HEATING

To describe the Brunel energy absorption by a large atomic cluster, we first consider each small part of the cluster surface as a plane irradiated by a superintense femtosecond laser pulse. This is valid if the excursion length F/ω^2 of a free electron ejected by laser field from the cluster is less than the cluster radius R. Here, F and ω are the field strength amplitude and field frequency, respectively. For example, if $R = 20$ nm (the number of Kr atoms is $N_a = 4.7 \cdot 10^5$ in such a cluster), $\hbar\omega = 1.5$ eV (Ti:Sapphire laser), then the peak laser intensity should be less than $5 \cdot 10^{16}$ W/cm^2 ($F < 1.2$ a.u). In practice, the inequality

$$F/\omega^2 \geq R$$

can be also permitted, because an electron is ejected from the cluster with zero velocity, and therefore it moves and returns to the cluster along the same curved electric field line.

Free electrons are produced at the leading edge of the laser pulse due to a single-ionization process. The local coordinate x is assumed to be directed along the normal to the cluster surface, and $x > 0$ is the region inside the cluster plasma. Inside the liquid cluster matter, the plasma frequency

$$\omega_p = \sqrt{4\pi n_e}$$

is large compared to the laser frequency ω, and hence the external electric field practically does not penetrate the cluster. Here, n_e is the electron number density. In addition, we assume that the cluster is sufficiently large, such that the outer ionization can be neglected, unlike in the case of inner ionization [9]. According to the Bethe rule for barrier-suppression outer ionization [9], the charge of the cluster ion (i.e., the number of ejected electrons) is

$$Q = 4F_{in}R^2.$$

The condition of a weak outer ionization

$$Q \ll N_e = n_e \frac{4\pi R^3}{3}$$

(N_e is the total number of electrons in the cluster) corresponds to the requirement that

$$F_{in}/\omega_p^2 \ll R.$$

This inequality is usually fulfilled because $\omega_p \gg \omega$. For example, in the case of a Kr cluster, we have $n_e = 2.0 \cdot 10^{-3}$ a.u. for single ionization, and $\omega_p = 0.160$ a.u. $\gg \omega = 0.055$ a.u. If $R = 20$ nm, the above inequality is violated only when $F_{in} > 10$ a.u and $F > 100$ a.u.

Following Brunel's approach [2], we assume the vacuum region for $x < 0$, where the normal component of the incident linearly polarized laser field

$$F(t) = F \sin\omega t$$

is present on the surface. Here,

$$F = F_0 \exp\left(-t^2/\tau^2\right)$$

is the Gaussian envelope of the laser pulse and τ is the pulse duration. The reflected field $F(t)$ coincides with the incident field within the laser wavelength λ from the cluster surface. We assume that the excursion length

$$F/\omega^2 < R \ll \lambda,$$

where λ is the laser wavelength. As the field increases for $t > 0$, electrons are pulled out during the first half of the laser period $0 < t < \pi/\omega$. The $(l+1)$th electron feels the total electric field strength $F(t) + F_l(t)$, where

$$F_l(t) = -4\pi \sum_{i=1}^{l} d\sigma_i = -4\pi \sum_{i=1}^{l} n_i(x_i) dx_i \qquad (1)$$

is the electric field strength produced by the previously ejected electrons and their images inside the cluster, $d\sigma_i$ is the surface number density of the ith electron, and $n_i(x_i)$ is the volume number density of the ejected ith electron ($d\sigma_i = n_i dx_i$). The electrons that are ejected after the $(l+1)$th electron do not contribute to Eq. (1) because these electrons and their images are on one side of the considered $(l+1)$th electron.

The quantity F_l is independent of the time t because the electric field produced by a uniformly charged plane is independent of the distance between this plane and the cluster surface. Hence, putting $t = t_l$ in Eq. (1), we obtain

$$F_l(t) = F_l(t_l) = -F \sin\omega t_l. \qquad (2)$$

The last relation follows from the statement that the total electric field vanishes on the cluster surface, $F(t) + F_l(t) = 0$ when $t = t_l$ and $x_l = 0$. Thus, the total electric field is equal to $F(t) + F(t_l)$ for the $(l+1)$th electron. The motion of this electron is described by the Newton equation

$$\frac{dv_l}{dt} = -F\left(\sin\omega t - \sin\omega t_l\right)$$

($l \gg 1$, and hence there is no real difference between the numbers l and $l+1$). We can integrate this equation to obtain the velocity of the lth electron under the initial condition of a cold ejected electron $v_l(t_l) = 0$:

$$v_l(t) = \frac{F}{\omega}\left[\cos\omega t - \cos\omega t_l + \omega(t - t_l)\sin\omega t_l\right]. \qquad (3)$$

We can integrate Eq. (3) to obtain the position of the lth electron under the initial condition $x_l(t_l) = 0$:

$$x_l(t) = \frac{F}{\omega^2}\left[\left(\sin\omega t - \sin\omega t_l\right) - \omega\left(t - t_l\right)\cos\omega t_l + \right.$$
$$\left. + \frac{\omega^2}{2}\left(t - t_l\right)^2 \sin\omega t_l\right]. \qquad (4)$$

The time instance for the return of the lth electron inside the cluster is determined from the universal implicit equation $x_l(t) = 0$, or

$$\sin\omega t - \sin\omega t_l = \omega\left(t - t_l\right)\cos\omega t_l - $$
$$- \frac{\omega^2}{2}\left(t - t_l\right)^2 \sin\omega t_l. \qquad (5)$$

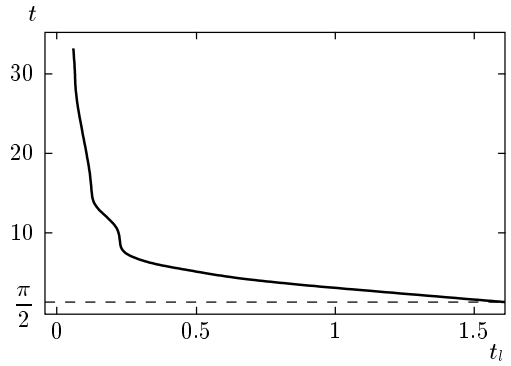

Fig. 1. The universal dependence of the returning time t on the time t_l of the electron ejection according to Eq. (5)

A nonzero ($t \neq t_l$) solution of this equation is possible only in the interval $0 < t_l < \pi/2\omega$ (the first quarter of the laser period). We restrict ourselves the range $t_l < t < 2\pi/\omega$; $t = t_l$ when $t_l = \pi/2\omega$ (no return), but $t > \pi/2\omega$ when $t_l < \pi/2\omega$. The dependence $t(t_l)$ is shown in Fig. 1. It is seen that small values $\omega t_l \ll 1$ correspond to large values of the returning time $t > 2\pi/\omega$. We neglect their contribution, although they slightly distort the electron ejection during the next laser period, because these electrons have small electron density n_l (see below Eq. (8)). The approximate solution of Eq. (5) is then given by

$$t \approx \frac{2}{\omega^2 t_l} \gg \frac{1}{\omega}.$$

We can repeat all operations during the next laser period analogously to the above consideration.

The absorbed energy over one laser cycle per unit square is given by [2]

$$E_e = \sum \frac{1}{2} v_l^2 n_l \, dx_l = \frac{1}{2} \int\limits_{\pi/2\omega}^{2\pi/\omega} v_l^3 n_l dt. \tag{6}$$

The electron number density n_l can be found by differentiating Eq. (1) with respect to t_l at a fixed value of t and taking Eq. (2) into account:

$$\frac{dF_l}{dt_l} = -4\pi n_l \frac{dx_l(t)}{dt_l} = -F\omega \cos \omega t_l. \tag{7}$$

Differentiating Eq. (4) with respect to t_l at a fixed value of t and substituting the result in Eq. (7), we obtain the quantity n_l :

$$n_l(t) = \frac{1}{2\pi \left(t - t_l\right)^2}. \tag{8}$$

Substituting Eqs. (3) and (8) in Eq. (6), we find

$$E_e = \frac{F^3}{4\pi\omega^3} \times \\ \times \int\limits_{\pi/2\omega}^{2\pi/\omega} \frac{\left[\cos \omega t - \cos \omega t_l + \omega (t - t_l) \sin \omega t_l\right]^3}{\left(t - t_l\right)^2} dt. \tag{9}$$

The integral is done numerically, and E_e can be written as

$$E_e = \frac{\eta}{8\pi\omega^2} \left(3F \cos \theta\right)^3, \tag{10}$$

where $\eta = 0.75$. In Eq. (10), we substituted the external field strength F far from cluster by the field strength at the cluster surface

$$F_s = 3F \cos \theta,$$

which is normal to the cluster surface at each surface point (under the condition that the electric field F_{in} inside the cluster is very small). Here, θ is the angle between the polarization of the linearly polarized laser field and the normal to the cluster surface.

The maximum number of returning electrons during one laser cycle per unit square is

$$N = \frac{F_s}{4\pi} = \frac{3F \cos \theta}{4\pi}.$$

The averaged energy ε of a hot electron is

$$\varepsilon = \frac{E_e}{N} = \frac{\eta \overline{(3F \cos \theta)^2}}{2\omega^2} = \frac{3\eta F^2}{2\omega^2},$$

i.e., it is of the order of the ponderomotive energy (as in a rescattering process for an atom [10], but with a different numerical coefficient). The maximum number of returning electrons during one laser cycle for the whole cluster is (also see Eq. (12) below)

$$N_r = 2 \int\limits_0^{\pi/2} N (2\pi R \sin \theta) R \, d\theta = \frac{3FR^2}{2}.$$

The number of free electrons inside the cluster is

$$N_e = n_e \frac{4\pi R^3}{3} = \frac{\omega_p^2 R^3}{3}.$$

We then have

$$\frac{N_r}{N_e} = \frac{9F}{2\omega_p^2 R}.$$

For example, when $R = 20$ nm, $F = 0.5$ a.u (the peak laser intensity is approximately equal to 10^{16} W/cm^2),

$\omega = 1.5$ eV, and $\omega_p = 0.16$ a.u. (single ionization of atoms in the Kr cluster), we obtain $N_r/N_e \approx 0.25$. The number of electrons heated during the laser pulse can be estimated by multiplying the quantity N_r/N_e by the number of laser periods $\omega\tau/2\pi = 54$ (at $\tau = 150$ fs). Thus, the conclusion can be made that all electrons are heated in the cluster during the laser pulse.

The mean free time of electron–electron collisions inside the Kr cluster,

$$\tau_{ee} = \frac{3T_e^{3/2}}{4\sqrt{2\pi}n_e \ln\Lambda}$$

($\ln\Lambda \sim 10$ is the Coulomb logarithm), is larger than the pulse duration $\tau = 150$ fs for the electron temperature $T_e > 1.5$ keV during the laser pulse. Therefore, there is no Maxwell distribution among electrons during the femtosecond laser pulse [11]. The kinetic energy of the heated electron in the peak of the laser pulse is $\varepsilon = 3\eta F^2/2\omega^2 \sim 2.5$ keV at $F = 0.5$ a.u.

The absorbed power I per unit square of the cluster surface can be found by dividing E_e over the laser period $2\pi/\omega$. Thus,

$$I = \frac{27\eta}{16\pi^2\omega}F^3\cos^3\theta. \tag{11}$$

We now integrate I over the cluster surface. The power W absorbed by the entire cluster is given by

$$W = 2\int\limits_0^{\pi/2} I\cos^3\theta(2\pi R\sin\theta)R\,d\theta = \frac{27\eta R^2}{16\pi\omega}F^3. \tag{12}$$

3. CLUSTER EXPANSION

The energy of laser radiation is first absorbed by the cluster electrons; then this energy transforms into the kinetic energy of the atomic ions. The cluster expansion is a nonequilibrium statistical process due to high expansion velocities. Thus, the increasing pressure of the electron gas is not compensated by the external medium. Therefore, the well-known expression $P_e dV$ (P_e is the pressure of the electron gas) of the equilibrium statistical physics is not applicable for derivation of the expansion work. Instead, we calculate the variation of the kinetic energy of atomic ions inside the expanding cluster. We assume that the velocity of the radial motion of atomic ions $v(r)$ is a linear function of the radial variable r:

$$v(r) = \frac{dR}{dt}\frac{r}{R}.$$

The kinetic energy of atomic ions in the spherical layer having the width dr is

$$dE_k = 4\pi r^2\frac{n_a M_a v^2(r)}{2}dr,$$

where M_a is the mass of an atomic ion and n_a is the number density of atomic ions. The total kinetic energy of cluster ions can be obtained by integration over r:

$$E_k = \int\limits_0^R 4\pi r^2\frac{n_a M_a v^2(r)}{2}dr = \frac{3}{10}N_a M_a\left(\frac{dR}{dt}\right)^2.$$

We took into account that the number density of atomic ions is

$$n_a = \frac{3N_a}{4\pi R^3},$$

and N_a is the total number of atoms in the cluster. The time derivative of this energy gives the expansion work produced per unit time:

$$\frac{dE_k}{dt} = \frac{3}{5}N_a M_a\frac{dR}{dt}\frac{d^2R}{dt^2}. \tag{13}$$

According to Eqs. (12) and (13), the cluster vacuum heating is determined from the energy balance equation

$$\frac{dE}{dt} = \frac{27\eta R^2}{16\pi\omega}F_0^3\exp\left(-\frac{3t^2}{\tau^2}\right) - \frac{3}{5}N_a M_a\frac{dR}{dt}\frac{d^2R}{dt^2}, \tag{14}$$

where $E(t)$ is the total thermal energy of the heated electrons inside the cluster as a function of time t. The cluster expansion is determined from the Newton equation

$$\frac{d^2R}{dt^2} = \frac{3P_e}{n_a M_a R}. \tag{15}$$

The electron pressure is

$$P_e = \frac{2E}{3V}.$$

This expression is also valid for nonequilibrium process of the cluster expansion. The electron pressure can be produced by both the electron–electron collisions and elastic reflections of electrons from the cluster surface (the latter occurs for high-energy electrons). Hence,

$$\frac{d^2R}{dt^2} = \frac{2E}{M_a N_a R}, \tag{16}$$

where

$$N_a = n_a V = \text{const}$$

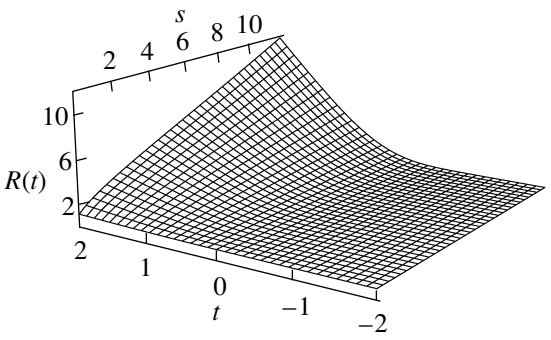

Fig. 2. The universal dependence of the cluster radius $R(t)$ (in units of the inital cluster radius R_0) on time t (in units of the pulse duration τ) for different values of the field parameter s (Eq. (17))

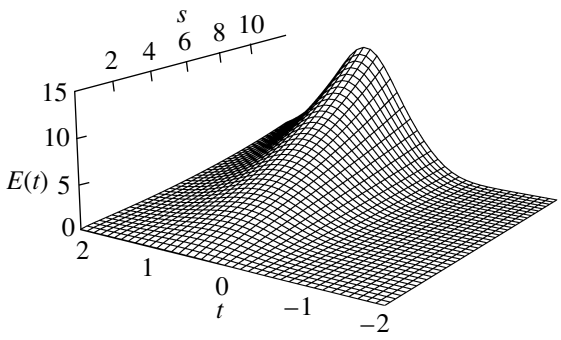

Fig. 3. The universal dependence of the absorption energy $E(t)$ (in units of $M_a N_a R_0^2/2\tau^2$) by a cluster on time t (in units of the pulse duration τ) for different values of the field parameter s

is the number of atomic ions in the cluster. Equations (14) and (16) are to be solved jointly under the initial conditions

$$R(-\infty) = R_0, \quad \frac{dR}{dt} = 0 \quad \text{at} \quad t \to -\infty,$$

$$E(-\infty) = 0.$$

We introduce the dimensionless radius $R/R_0 \to R$, the dimensionless time $t/\tau \to t$, the dimensionless electron energy

$$\frac{2\tau^2}{M_a N_a R_0^2} E \to E,$$

and the dimensionless field parameter

$$s = \frac{27\eta (F_0 \tau)^3}{16\pi\omega M_a N_a}. \tag{17}$$

Then the dimensionless universal equations can be written as

$$\begin{aligned} &\frac{dE}{dt} = sR^2 \exp(-3t^2) - \frac{6E}{5R}\frac{dR}{dt}, \\ &\frac{d^2R}{dt^2} = \frac{E}{R} \end{aligned} \tag{18}$$

and the initial conditions become

$$R(-\infty) = 1, \quad \frac{dR}{dt} = 0 \quad \text{at} \quad t \to -\infty, \quad E(-\infty) = 0.$$

It is seen that the vacuum heating of cluster electrons and the cluster expansion are determined by only one universal dimensionless field parameter s, Eq. (17). In Figs. 2 and 3, the functions $R(t)$ and $E(t)$ are shown for various values of the parameter s. It should be noted that the multiple inner ionization of atoms inside the cluster does not change the obtained results. It decreases the average energy of a hot electron only. It follows from Eq. (18) that the velocity of cluster expansion

$$V = \frac{dR}{dt} = \text{const} \quad \text{as} \quad t \to +\infty,$$

and

$$E(t \to +\infty) \sim t^{-6/5} \to 0$$

due to adiabatic cooling of the cluster electrons after the end of the laser pulse.

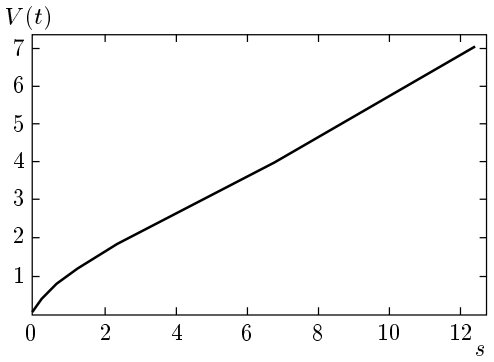

Fig. 4. The final velocity of the cluster expansion $V(t)$ as a function of the field parameter s as $t \to +\infty$

In Fig. 4, we present the final dimensionless velocity of the cluster expansion $V(t \to +\infty)$ as a function of the field parameter s at $t \to +\infty$. It is seen that this dependence can be approximated by the simple linear dependence $V = 0.8s$.

For the laser–Kr cluster interaction at $F_0 = 1$ a.u., $R_0 = 20$ nm, and $\tau = 100$ fs, we find $s = 7.0$. Then $V = 5.6$ a.u. In the usual units, we find $V = 5.6R_0/\tau$. It

then follows that $V \approx 1.1$ nm/fs, which is in agreement with Fig. 3 in Ref. [12] for the same values of the parameters. Hence, in this example, the maximum kinetic energy of Kr ions is approximately equal to 530 keV. Thus, most of the electron heating energy transforms into the energy of cluster ion expansion; the kinetic energy of the heated electron in the peak of the laser pulse is

$$\varepsilon = \frac{3\eta F^2}{2\omega^2} \approx 10 \text{ keV} \quad \text{at} \quad F = 1 \text{ a.u.}$$

4. CONCLUSION

The hydrodynamic expansion of large Xe clusters ($1.5 \cdot 10^5$ atoms per cluster) was observed at the irradiation by a laser pulse with the peak intensity approximately 10^{16} W/cm^2 [13]. The duration of the laser pulse was $\tau = 200$ fs. The authors also took the asymmetric pressure of the laser field into account in addition to the hydrodynamic pressure. It can be effective at plasma resonance when the Mie frequency coincides with the laser frequency. The field pressure produces an asymmetric cluster expansion.

Electron kinetic energy spectra were measured in [14] from the interaction of Kr and Xe clusters with a high-intensity 800 nm femtosecond laser pulse. The sizes of clusters were 10^4 and $2 \cdot 10^6$ atoms per cluster. The peak intensity was $5 \cdot 10^{16}$ W/cm^2 at the shortest pulse duration $\tau = 50$ fs. The cutoff in the electron energy spectrum was found to be at $\varepsilon = 6$ keV. According to our approach, the cutoff for electrons inside the cluster is

$$\varepsilon = \frac{3\eta F_0^2}{\omega^2} \approx 14 \text{ keV}.$$

The difference is explained by a decrease of the electron energy due to the adiabatic decrease of the laser field strength when the laser pulse turns off (in accordance with the Lawson–Woodward theorem, see also [15]). This cooling is confirmed by numerical simulation [16] of the interaction of a Xe cluster with a laser pulse ($\lambda = 780$ nm, $\tau = 260$ fs, $4 \cdot 10^{15}$ W/cm^2).

Hot electron generation by the vacuum heating process has been studied in the interaction of 150 fs, 5 mJ, 800 nm p-polarized laser pulses with solid targets [17]. The measurements have suggested that the «vacuum heating» is the main heating process for hot electrons with high energies. The energy of the vacuum-heated hot electrons has been found to be higher than the prediction from the scaling law of resonance absorption. Particle-in-cell simulations have confirmed that hot electrons are mainly generated by the vacuum heating process under certain experimental conditions.

Spectra of energetic electrons in the 100 keV range were measured from the interaction of intense femtosecond laser pulses with clusters of xenon or argon [18]. The interaction of 28 fs pulses with cluster targets revealed quite different results with respect to the applied laser intensity. At the laser intensity 10^{16} W/cm^2, the absorption by xenon clusters was about 25 %; however, at the laser intensity 10^{17} W/cm^2, the laser energy absorption drastically increased to 78 %, and the efficient coupling between the laser pulse and cluster target produced electrons with the energy as high as 500 keV. The estimated hot electron temperatures ranged from about 30 to 90 keV depending on atoms.

The Mie resonance is effective only during a very short time (2–3 fs) because of the very fast cluster expansion. Therefore, a short increase of the laser field at the resonance does not result in significant electron heating. The Mie resonance only appears in the self-similar expansion model in [1], and results from the calculation of the dipole moment. In Fig. 7 in Ref. [1], the electron energy as a function of time has a sharp and narrow peak because of the Mie resonance. Then the electron energy strongly decreases, such that the Mie resonance does not actually influence the final electron heating in accordance with the conclusion in the previous section.

In conclusion, the vacuum mechanism suggested by Brunel for irradiation of a planar solid surface by a high-intensity laser pulse is generalized to the case of large spherical clusters with the cluster hydrodynamic expansion taken into account. The universal expressions have been obtained for the absorbed laser energy by a cluster and for the radius of the expanding cluster as functions of time. The absorption of laser energy and the cluster expansion are determined by only one dimensionless field parameter s, Eq. (17).

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