# Collisional versus collisionless resonant and autoresonant heating in laser-cluster interaction

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When a hot cluster expands, a transient matching between the plasma frequency and the laser frequency has been predicted, observed, and analyzed recently. The associate energy transfer to the electrons has been described as an enhanced collisional absorption. However, for hot plasmas the collision frequency is small and a collisionless resonant heating is more efficient. We set up and solve the problem of resonant collisional and collisionless cluster heating taking into account cluster expansion, laser pulse duration and pulse chirping. Moreover, we identify an efficient autoresonant mechanism of collisionless heating with a chirped laser pulse when the crossing between the plasmon frequency and the laser frequency is degenerate and the time derivatives of these two frequencies are equal at the crossing time. Transition between collisional regime of cluster heating and collisionless one is discussed.

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## I. INTRODUCTION

High-power laser-plasma experiments usually use three types of targets: solid, gaseous, and clusters. Cluster targets have many advantages over solid and gaseous targets. Solid targets provide dense expanding plasma but suffer from an intrinsic drawback due to the geometry of the coupling, the conductive cooling, and the overdense part of the expanding plasma. On the other hand, the coupling to a gaseous target is realized through the full volume of the media, but, because of the low density does not provide an efficient transfer of energy from the laser to the plasma. In between these two extremes, clusters offer the advantage of a volume penetration of the laser at a rather high density and give rise to a strong coupling of laser energy to the particles, much stronger than that seen with isolated atoms or molecules.

The irradiation of atomic clusters by short ($\leqslant 1$ ps) intense ($>10^{15}$ W/cm$^2$) laser pulses leads to formation of a hot dense plasma and to the manifestation of new high energetic phenomena. Explosions of noble-gas clusters have given rise to ions with energies up to several MeV [1] and tens keV electrons [2]. X-ray emission from exploding clusters has been investigated and the yields seen to be comparable to that of solid targets, with x rays in the keV range observed [3]. Therefore, the hot dense plasma produced in laser-cluster interaction is a promising, compact source of x rays for applications including next generation extreme ultraviolet lithography [4], extreme ultraviolet and x-ray microscopy [5], and x-ray tomography [6]. Recently, nuclear fusion has been demonstrated using collisions of fast ions produced in the rapid expansion of laser-heated deuterium cluster plasmas [7]. It was also shown that rare-gas clusters can emit high-order harmonics with a significantly higher efficiency than that produced from atomic samples with the same density [8,9].

"Nanoplasma" model is used to study laser-cluster interaction [10]. This model describes laser-cluster interaction as spherical expanding plasma in laser field. It suggests that there is a resonance between the laser field and cluster plasma oscillations when cluster plasma density is equal to three times the critical electron density $n_{cr}$. The critical electron density is defined as the density at which the plasma frequency equals the laser frequency. There are two moments when this resonance can occur: the first moment is during the rapid ionization in the leading edge of the laser pulse, as the electron density increases through $3n_{cr}$ up to solid density, and a later moment as the expanding cluster plasma density decreases back through $3n_{cr}$. The laser field in the cluster is strongly enhanced at the resonance. This leads to the dramatic enhancement in collisional absorption [10].

It is clear that there is the optimal laser pulse duration when the laser peak is near the resonance point. Since the cluster size determines the cluster expansion dynamics, the optimal pulse width depends on the cluster size. This fact has been confirmed in experiments [11,12] that can be also viewed as the evidence of the resonance phenomenon in laser-cluster interaction. Another experimental evidence is that the heating of atomic clusters can be enhanced by using a correctly timed sequence of two high-intensity pulses [13].

At the initial stage of interaction, when the cluster density is high and the electron temperature is low, the heating is caused by inverse bremsstrahlung (collisional absorption) [14]. Moreover inverse bremsstrahlung absorption is significantly enhanced in cluster plasma because of the collective effects, which are absent in ordinary plasmas [15]. To calculate cluster heating, the collisional absorption of laser energy in a cluster is considered in the nanoplasma model [see, e.g., Eq. (19) in Ref. [10] or Eqs. (2) and (3) in Ref. [13]]. However electron temperature growth and cluster expansion lead to the suppression of the inverse bremsstrahlung and collisionless heating becomes dominant. Contrary to the collisional heating when the laser energy is directly absorbed by the interparticle collisions, collisionless heating means that a part of the laser energy is converted into the energy of the cluster nanoplasma oscillations. Collisionless resonant absorption in plasma has been well studied [16,17]. There are some generalizations of the nanoplasma model [18,19] but complexity of the generalized models makes the analytic treatment difficult. The motivation of our work is to extend the simple analytic estimates for the rate of collisional absorption in the framework of the nanoplasma model [10] to the regime of collisionless absorption and to include several important effects: cluster expansion, laser pulse duration, and laser pulse chirping. Another objective of the paper is to estimate the threshold of transition from collisional to collisionless regime of cluster heating.

The paper is organized as follows. In Sec. II the expression for the rate of collisional absorption in cluster plasma is derived in the framework of the ‘‘nanoplasma’’ model and the effect of laser pulse duration and pulse chirping on the absorption is studied. In Sec. III, the collisionless absorption in expanding cluster plasma is analyzed. The energy absorbed in cluster plasma is calculated in the resonant and autoresonant regimes of collisionless absorption in Secs. IV and V, respectively. In Sec. VI the transition from the collisional regime of cluster heating to the collisionless one is discussed and a summary discussion is presented.

## II. COLLISIONAL ABSORPTION

After ionization the atomic cluster can be considered as a nanoplasma and the free electrons of this plasma drop oscillate in the electric field of the laser pulse. Following the nanoplasma model [10] let us consider a small quasineutral spherical plasma with density $n$. If the electron sphere is displaced with respect to the ion sphere, this charge separation creates an electric field inside the sphere. As the electric field inside a homogeneous charged sphere is proportional to the distance to the center of the sphere, the electric field of space charge, $\mathbf{E}_{sc}$, resulting from the relative displacement between the two homogeneous electronic and ionic spheres is proportional to this displacement between the two spheres:

$$\mathbf{E}_{sc}=\frac{ne}{3\varepsilon_0}\mathbf{r}, \tag{1}$$

where $-e$ is the electron charge. These polarization fields add up to the incident laser field. As the cluster size is smaller than the laser wavelength, we can use the dipolar approximation to describe the laser wave: $\mathbf{E}\cos(\omega t)$. The electron population will respond to the sum of the space charge and laser field, $\mathbf{E}_{sc}+\mathbf{E}\cos(\omega t)$, through inertia and will generate a driven plasmon oscillation:

$$\frac{d^2\mathbf{r}}{dt^2}-\nu\frac{d\mathbf{r}}{dt}+\Omega^2\mathbf{r}=-\frac{e}{m}\mathbf{E}\cos(\omega t), \tag{2}$$

where $m$ is the electron mass, $\Omega=\omega_p/\sqrt{3}$ is the frequency of cluster plasma oscillations, $\omega_p$ is the plasma frequency, and $\nu$ is the momentum transfer frequency. This laser driven plasmon oscillation gives rises to both a reactive current that determines the dispersion of the cluster media and an active current that determines the absorption of the cluster media. We consider the density of laser energy

$$\frac{dU}{dV}=\varepsilon_0\frac{E^2}{2}. \tag{3}$$

The density of absorbed power $d^2U/(dVdt)$ is given by the work done by the laser fields on the electron population averaged over one period of the oscillation

$$\frac{d^2U}{dVdt}=-ne\left\langle \mathbf{E}\cdot\frac{d\mathbf{r}}{dt}\right\rangle=\mathrm{Re}\left[\frac{i\omega\omega_p^2}{\Omega^2-\omega^2-i\omega\nu}\right]\varepsilon_0\frac{E^2}{2}. \tag{4}$$

This finally leads to the classical result used to study laser-cluster interaction [10]:

$$\frac{d^2U}{dVdt}=\frac{9}{2}\frac{\nu\omega^2\omega_p^2}{\omega_p^2(\omega_p^2-6\omega^2)+9\omega^2(\omega^2+\nu^2)}\varepsilon_0E^2. \tag{5}$$

This absorbed power is maximum when $\omega=\Omega$. On the other hand, collisional heating is efficient when $\omega\sim\nu$. Thus the most favorable ordering for heating would be $\omega\sim\nu\sim\sqrt{3}\omega_p$. Unfortunately the ratio $\omega_p/\nu$ is a fundamental characteristic of the plasma and is proportional to the number of electrons in the Debye sphere, so the ordering of cluster plasma is $\omega_p\gg\nu$. Nevertheless, efficient heating of the cluster with short intense laser pulse has been observed and analyzed in terms of collisional heating according to the formula. The main feature of this collisional heating is the occurrence of a transient resonance when $\omega\sim\sqrt{3}\omega_p(t)$ as the plasma expansion leads to a continuous decrease of the plasma frequency. Laser field and energy absorption are strongly enhanced at the resonance.

The variation of laser field is neglected in above calculations. However the real laser-cluster experiments deal with laser pulses. To take into account laser pulse duration and laser pulse chirping we write the laser field as follows:

$$E(t)=E\exp\left(-\frac{t^2}{2T^2}\right)\cos\left(\omega t+\dot{\omega}\frac{t^2}{2}\right), \tag{6}$$

where $T$ is the laser pulse duration and, we take into account pulse chirping using parameter $\dot{\omega}$. The Fourier transform of $E(t)$ is given by the expression

$$E_p=E\left\{\frac{\exp\left[-\frac{(p-\omega)^2}{2T^{-2}-2i\dot{\omega}}\right]}{2\sqrt{2\pi}\sqrt{T^{-2}-i\dot{\omega}}}+\frac{\exp\left[-\frac{(p+\omega)^2}{2T^{-2}+2i\dot{\omega}}\right]}{2\sqrt{2\pi}\sqrt{T^{-2}+i\dot{\omega}}}\right\}. \tag{7}$$

The density of absorbed energy in the cluster can be calculated as

$$\frac{dU}{dV}=-ne\int_{-\infty}^{+\infty}\mathbf{E}\cdot\frac{d\mathbf{r}}{dt}dt=i2\pi\varepsilon_0\omega_p^2\int_{-\infty}^{+\infty}dp\,\frac{pE_pE_{-p}}{\Omega^2-p^2-ip\nu}. \tag{8}$$

Assuming that the laser pulse is not too short $(\omega\sqrt{T^2+1/\dot{\omega}}\gg1)$, we can rewrite last equation as follows

$$\frac{dU}{dV} \simeq \frac{\varepsilon_0 \nu \omega_p^2 T^2 E^2}{2\sqrt{1+\dot{\omega}^2 T^4}} \int_{-\infty}^{+\infty} dx \frac{x^2 \exp\left[-\frac{T^2(x-\omega)^2}{1+\dot{\omega}^2 T^4}\right]}{(\Omega^2 - x^2)^2 + x^2 \nu^2}. \quad (9)$$

As the laser field enhancement and effective collisional absorption occur at the resonance we assume that $\omega \simeq \Omega$ and the collisionality is weak $\omega \gg \nu$. Then we get

$$\frac{dU}{dV} \simeq \frac{\varepsilon_0 \nu \omega_p^2 T^2 E^2}{2\sqrt{1+\dot{\omega}^2 T^4}} \int_{-\infty}^{+\infty} dx \frac{\exp\left[-\frac{T^2 x^2}{1+\dot{\omega}^2 T^4}\right]}{4x^2 + \nu^2}$$
$$= \frac{\pi \varepsilon_0 \omega_p^2 T^2 E^2}{4\sqrt{1+\dot{\omega}^2 T^4}} [1 - \mathrm{erf}(\mu)] \exp(\mu^2), \quad (10)$$

where $\mathrm{erf}(\mu)$ is the probability integral [20] and $\mu = T\nu/(2\sqrt{1+\dot{\omega}^2 T^4})$.

Function $[1-\mathrm{erf}(\mu)]\exp(\mu^2)$ is monotonically decreasing from 1 for $\mu = 0$ to $1/(\mu\sqrt{\pi})$ for $\mu \to \infty$. Value $(dU/dV)/(T\sqrt{\pi})$ reduces to the density of absorbed power defined by Eq. (5) at the resonance $\omega \simeq \Omega$ in the limit $T \to \infty$,

$$\frac{dU}{dVdt} = \frac{\omega_p^2 \varepsilon_0 E^2}{2\nu}. \quad (11)$$

In the reverse limit $\mu \ll 1$ the laser energy absorbed in unit cluster volume does not depend on collisional frequency

$$\frac{dU}{dV} = \frac{3\pi \varepsilon_0 E^2 (\omega T)^2}{4\sqrt{1+\dot{\omega}^2 T^4}}. \quad (12)$$

It follows from Eq. (12) that the absorption regime is collisionless. More general results for resonant collisionless absorption will be derived in the following sections by use of the Hamiltonian approach. It follows from Eq. (10) that for short laser pulse the collisional absorption rate can essentially differ from the standard result, Eq. (5).

## III. COLLISIONLESS RESONANT ABSORPTION

Let us now consider resonant collisionless absorption in a cluster plasma. This absorption is caused by the resonance excitation of the plasma oscillation by the laser field. In the following, except the final results, we use the system of units $e = m = c = 1$. In the nanoplasma model the electron dynamics in weak laser field can be described by the Hamiltonian

$$H(p,q,t) = \frac{p^2}{2} + \frac{\Omega^2(t) q^2}{2} + qE(t)\cos\varphi(t), \quad (13)$$

where $p$ and $q$ are the momentum and coordinate of electrons in the cluster, $E(t)\cos\varphi(t)$ is the laser field. We take into account the fact that frequency of the cluster plasma oscillations, $\Omega(t)$, depends on time because of the cluster expansion. To introduce more convenient canonical variables, we can perform canonical transformation by generating function

$$F(q,Q,t) = \frac{iQ^2}{2} - i\sqrt{2\Omega(t)}qQ + \frac{i\Omega(t) q^2}{2}. \quad (14)$$

The relations between the old canonical variables $(p,q)$ and new one $(P,Q)$ are

$$P = -\frac{\partial F}{\partial Q} = i\frac{\sqrt{\Omega} q}{2} + \frac{p}{\sqrt{2\Omega}}, \quad Q = \frac{\sqrt{\Omega} q}{2} + i\frac{p}{\sqrt{2\Omega}},$$
$$p = \frac{\partial F}{\partial q} = \sqrt{\frac{\Omega}{2}}(P - iQ), \quad q = \frac{1}{\sqrt{2\Omega}}(Q - iP). \quad (15)$$

The Hamiltonian in new canonical variables can be written as follows:

$$H = -i\Omega PQ - \frac{i\dot{\Omega}}{4\Omega}(P^2 + Q^2) + \frac{Q - iP}{\sqrt{2\Omega}} E(t)\cos\varphi(t). \quad (16)$$

The dynamics of the electron population in the cluster is defined by the Hamiltonian equations

$$\frac{dQ}{dt} = -i\Omega(t) Q - i\frac{E(t)}{\sqrt{2\Omega(t)}}\cos\varphi(t) - \frac{i\dot{\Omega}}{2\Omega}P,$$
$$\frac{dP}{dt} = i\Omega(t) P - \frac{E(t)}{\sqrt{2\Omega(t)}}\cos\varphi(t) + \frac{i\dot{\Omega}}{2\Omega}Q. \quad (17)$$

The time of plasma frequency variation in the cluster is of the order of the cluster expansion time that is approximately equal to the inverse plasma ion frequency [7]. This time is much less than the period of plasma electron oscillations. So we can conclude that $\dot{\Omega}/\Omega^2 \ll 1$ and can neglect the last term in Hamiltonian equations. Then the equations can be solved and the amplitude of the excited oscillations can be calculated:

$$Q(t) = -i\exp\left(-i\int^t \Omega d\xi\right)\int_{-\infty}^t \frac{E(\tau)\cos\varphi(\tau)}{\sqrt{2\Omega(\tau)}} \times \exp\left(i\int^\tau \Omega d\xi\right) d\tau,$$
$$P(t) = -\exp\left(i\int^t \Omega d\xi\right)\int_{-\infty}^t \frac{E(\tau)\cos\varphi(\tau)}{\sqrt{2\Omega(\tau)}} \times \exp\left(-i\int^\tau \Omega d\xi\right) d\tau. \quad (18)$$

The change in the energy per electron is equal to

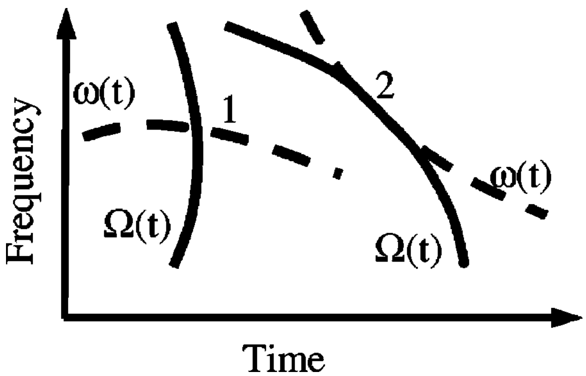


FIG. 1. Schematic of the resonance regime (1) and autoresonance regime (2) in $\omega$-$t$ plane.

$$\Delta U = \Omega \left| \int_{-\infty}^{+\infty} \frac{E(t)\cos\varphi(t)}{\sqrt{2\Omega(t)}} \exp\left( i \int^{t} \Omega d\xi \right) dt \right|^2 . \quad (19)$$

Using the obtained expression we will analyze two regimes of cluster plasma heating: collisionless resonant heating and collisionless autoresonant heating.

## IV. COLLISIONLESS RESONANT HEATING

Let laser pulse $E(t) = E\exp[-t^2/(2T^2)]\cos\varphi(t)$ interact with an expanding ionized cluster. At the resonance moment $t = t_0$ when $\Omega \simeq \dot{\varphi} \simeq \omega$ we can expand both cluster plasmon frequency

$$\Omega(t) = \Omega + \dot{\Omega}(t - t_0) + \cdots \quad (20)$$

and laser field phase

$$\varphi(t) = \varphi_0 + \Omega(t - t_0) + \dot{\omega}\frac{(t-t_0)^2}{2} + \cdots . \quad (21)$$

Using Eq. (19) the absorbed energy per unit cluster volume can be calculated and written in usual units as follows:

$$\frac{dU_{res}}{dV} = n_e \Delta U = \frac{3\pi\varepsilon_0 E^2 (T\omega)^2}{4\sqrt{\alpha^2+1}} \exp\left( -\frac{2\alpha^2 \xi_0^2}{\alpha^2+1} \right), \quad (22)$$

where $\xi_0 = t_0/T$ and parameter $\alpha = T^2(\dot{\Omega} - \dot{\omega})$.

It follows from Eq. (22) that the absorption is significantly reduced when the resonance does not occur at the maximum of laser field. Notice that if the resonance occurs at the laser pulse maximum ($t_0 = 0$) and the cluster expansion is neglected ($\dot{\Omega} = 0$), then Eq. (22) turns in Eq. (12) derived in electrodynamic approach.

## V. COLLISIONLESS AUTORESONANT HEATING

Let us now consider an autoresonant regime of cluster heating. Autoresonance (adiabatic nonlinear phase locking and synchronization) is a remarkable phenomenon of nonlinear physics when a driven dynamic system stays in resonance with the driving oscillation or wave continuously despite variation of system's parameters. In our problem, autoresonance means that not only the laser frequency and the frequency of cluster plasma oscillations are close to each other at the resonance, but also the first derivatives of these frequencies with respect to time are close to each other. The difference between the resonance and autoresonance is illustrated in Fig. 1. If the autoresonant condition is fulfilled

$$\Omega - \omega \simeq 0, \quad \dot{\Omega} - \dot{\omega} \simeq 0, \quad (23)$$

then the next term in expansions (20) and (21) has to be taken into account. Using Eq. (19) the absorbed energy per unit cluster volume can be calculated for the autoresonant regime

$$\frac{dU_{auto}}{dV} = \frac{\varepsilon_0 E^2 (T\omega)^2}{2\beta^2} \exp\left( \frac{2}{3\beta^2} \right) K_{1/3}^2 \left( \frac{1}{3\beta^2} \right), \quad (24)$$

where $\beta = T^3(\ddot{\Omega} - \ddot{\omega})$. To derive Eq. (24) we assume for simplicity that the resonance occurs at the laser pulse maximum ($t_0 = 0$). It should be noted that in the case of the short laser pulse ($\alpha \ll 1$ and $\beta \ll 1$) Eqs. (12), (22), and (24) reduce to the same expression

$$\frac{dU_{auto}}{dV} = \frac{3}{4}\pi\varepsilon_0 E^2 (T\omega)^2 . \quad (25)$$

In this limit, cluster expansion and pulse chirping do not affect cluster heating. In the opposite limit $\beta \gg 1$, Eq. (24) reduces to the form

$$\frac{dU_{auto}}{dV} = \frac{\varepsilon_0 E^2 \pi^2 (T\omega)^2}{6^{1/3}\beta^{2/3}\Gamma^2(2/3)}, \quad (26)$$

where $\Gamma(x)$ is the gamma function [20]. To compare heating efficiency in the resonant and autoresonant regimes we can assume $t_0 = 0$, $\ddot{\omega} = 0$, $\beta \simeq T^3\omega/\tau_{\exp}^2$, and $\alpha \simeq T^2\omega/\tau_{\exp}$, where $\tau_{\exp}$ is the characteristic time of cluster expansion. Then using Eqs. (22) and (26) the ratio of absorbed energy in the autoresonant regime to that in the resonant regime is given by the relation

$$\eta = \frac{U_{auto}}{U_{res}} \simeq 2.5(\omega\tau_{\exp})^{1/3} . \quad (27)$$

As $\omega\tau_{\exp} \gg 1$ for typical laser-cluster experiments then autoresonant regime of heating is more effective than the resonant one.

## VI. CONCLUSIONS AND DISCUSSIONS

Let us now discuss the transition from the collisionless regime of heating to the collisional one. The general solution of Eq. (2) for slowly varying $\Omega(t)$ can be presented in the form of the Duhamel integral [21]

$$\mathbf{r}(t) = \int_{-\infty}^{t} \frac{\mathbf{E}(t') e^{\nu(t'-t)}}{\sqrt{\Omega^2(t) - \nu^2}} \sin\left( \int_{t'}^{t} \sqrt{\Omega^2(\xi) - \nu^2} d\xi \right) dt' . \quad (28)$$

Using the Duhamel integral the density of absorbed energy in cluster can be written as follows:

$$\frac{dU}{dV} = -ne\int_{-\infty}^{+\infty}\mathbf{E}\cdot\frac{d\mathbf{r}}{dt}dt$$
$$\simeq -ne\int_{-\infty}^{+\infty}dt\int_{-\infty}^{t}\mathbf{E}(t)\cdot\mathbf{E}(\tau)e^{\nu(\tau-t)}\cos\left(\int_{\tau}^{t}\Omega(\xi)d\xi\right)d\tau, \tag{29}$$

where $\Omega \gg \nu$ and $\dot{\Omega}/\Omega^2 \ll 1$ are assumed. Taking the laser field in form (6) and expanding cluster plasmon frequency near resonance $\Omega \simeq \omega + \dot{\Omega}t$, the density of absorbed energy can be rewritten in the form

$$\frac{dU}{dV} \simeq -\frac{neE^2}{2}\int_{-\infty}^{+\infty}dt\int_{-\infty}^{t}d\tau \exp\left(-\frac{t^2+\tau^2}{2T^2}\right)$$
$$\times e^{\nu(\tau-t)}\cos\left[(\dot{\omega}-\dot{\Omega})\frac{t^2-\tau^2}{2}\right], \tag{30}$$

where nonresonant terms are neglected. It is seen from Eq. (30) that the cluster expansion rate can be taken into account as a correction to the rate of laser chirping $\dot{\omega}$ through parameter $(\dot{\omega}-\dot{\Omega})$ [as in Eq. (22) for collisionless resonant heating]. Therefore we can replace $\dot{\omega}$ with parameter $(\dot{\omega}-\dot{\Omega})$ in Eq. (10) to include the cluster expansion effect in the expression for the absorbed energy per unit cluster volume. Then the general formula for collisional and collisionless resonant heating in the expanding cluster can be rewritten in the form

$$\frac{dU}{dV} \simeq \frac{\pi\varepsilon_0\omega_p^2T^2E^2}{4\sqrt{1+T^4(\dot{\Omega}-\dot{\omega})^2}}[1-\mathrm{efr}(\mu)]\exp(\mu^2), \tag{31}$$

where $\mu = (1/2)T\nu/\sqrt{1+T^4(\dot{\Omega}-\dot{\omega})^2}$.

It follows from Eq. (31) that in the limit $\mu \gg 1$ collisional absorption is dominant. The expression for power density absorbed by collisions in the expanding cluster reduces to Eq. (11) in this limit. In the opposite limit of collisionless resonant heating $\mu \ll 1$, Eq. (31) reduces to Eq. (22) for $t_0 = 0$. We have numerically solved Eq. (2) using approximation $\Omega(t) = \omega[1+\arctan(\dot{\Omega}t/\omega)]$ for the frequency of the cluster plasmon oscillation. The results are presented in Fig. 2. It is seen from Fig. 2 that relation (31) is in fairly good agreement with numerical simulation. Neglecting laser chirping $\dot{\omega}=0$ we can rewrite the criterion for collisionless absorption in the expanding cluster as $\mu \simeq \nu/(2T\dot{\Omega}) \ll 1$ in the limit $T^2\dot{\Omega} \gg 1$. As for typical laser-cluster experiments ($T\omega \simeq 100$–200, $\nu/\omega \simeq 0.03$, $\omega\tau_{\mathrm{exp}} \sim 200$ [11,13]) $\mu \simeq (\nu/\omega)(\tau_{\mathrm{exp}}/T) \ll 1$ we can conclude that collisionless absorption of laser energy in the cluster plasma is more efficient than the collisional one for the late stage of interaction.

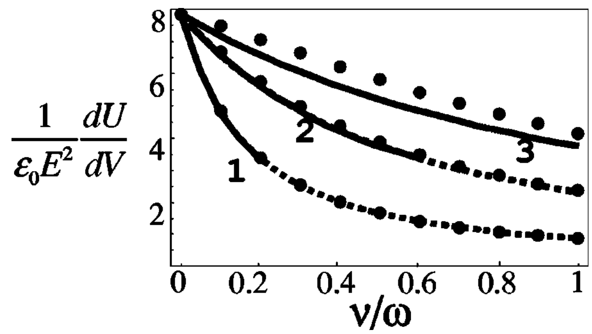


FIG. 2. Density of absorbed energy normalized to the density of laser energy $\varepsilon_0E^2/2$ versus normalized collisional frequency $\nu/\omega$ for $\omega\tau_{\mathrm{exp}}=10^3$, $T\omega=100$ (curve 1), $T\omega=300$ (curve 2), $T\omega=600$ (curve 3) in the collisional regime ($\mu>1$, dashed lines) and in the collisionless regime ($\mu<1$, solid lines). The same dependence calculated by the numerical solution of Eq. (2) (circles).

In conclusion we have considered collisional and collisionless heating in a cluster plasma in the framework of the nanoplasma model. First we have studied the dependence of the collisional absorption on the laser pulse duration and chirping. Then collisionless resonant absorption in an expanding cluster is considered. An efficient autoresonant regime of collisionless heating is identified and analyzed. A simple analytic estimate for the threshold of the transition from a collisional regime to a collisionless one is derived. It is shown that the collisionless regime of absorption is dominant for the late stage of laser-cluster interaction.

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