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Energy deposition of intense femtosecond laser pulses in Ar clusters

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Abstract. The transmission of femtosecond laser pulses in the Ar atomic-clusters is studied, and the absorption of the laser energy is calculated using a new theoretical model. Then the relevant physics parameters including the continuous winded range, the maximum penetration depth and the stopping time, have been calculated. Thus, we re-examine theoretically the possibility of this model.

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Key words: femtosecond laser pulses, cluster, energy deposition

1 Introduction

The advent of the chirped-pulse amplification (CPA) technique, coupled with the development of solid-state lasers capable of delivering ultra-short pulses, has opened the new field of ultrahigh-intensity laser physics. Researches on the interactions between clusters and intense femtosecond laser pulse have recently been a hot field [1-5]. The hot dense plasma created by the irradiation atomic clusters by short, intense laser pluses is a promising, compact source of x rays for applications including next generation extreme ultraviolet lithography, x-ray microscopy, ang x-ray tomography [6]. Atomic clusters formed in supersonic expansion of a high-pressure gas into vacuum have been proposed recently as an alternative solution combining the advantaged of both gaseous and solid targets. In particular, a rare-gas cluster that is classified as an intermediate state between isolated atoms and bulk solid-state matter has attracted considerable attention as a target [7], because it shows unique properties such as efficient absorption of laser photons leading to Coulomb explosions of a cluster [8], generation of bright x-ray radiation [9] and

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highly charged atomic ions, and formation of energetic ions up to MeV. For large clusters, Ditmire *et al*. demonstrated DD fusion induced by the Coulomb explosion of deuterium clusters in a field of 10^{16}W/cm^2 [10].

The interaction of ultraintense laser pulses and gas clusters contains three processes: the atom ionization, the energy absorption of laser pulses, and the Coulomb explosion of the clusters. There are many mechanisms to explain these processes, however, each model can fit the phenomena partly, a more detailed model of the laser-cluster interaction is required. When Ar clusters with 5×10^4 atoms and the radius of 13.4 nm irradiated by ultraintense ($I\geq10^6$ W/cm^2) and ultrafast (duration $\sim$ 10-100 fs) laser pulses, the charged atom ions can up to Ar^{8+} [11]. And above 90% of the laser energy is transferred to the kinetic energy of the cluster plasma [12, 13]. In this article, the transmission of femtosecond laser pulses in the Ar atomic-clusters is studied. Ultraintense laser can produce the relativistic electron beam (REB) and then the REB energy is delivered to the plasma. Then the relevant physics parameters including the continuous winded range, the maximum penetration depth and the stopping time, have been calculated. Thus, we re-examine theoretically the possibility of this model.

2 Energy deposition of intense femtosecond laser pulses in Ar clusters

2.1 Main energy loss mechanism [14]

The REB energy range considered is fixed by the laser irradiance through the relationship

$$T(keV)=511\{[1+0.007(I/I_{16})\lambda_\mu^2]^{1/2}-1\} \tag{1}$$

where, λ_μ is laser wavelength in unit of μm. Here we assume $\lambda_\mu=1\mu$m. I_{16} is the laser intensity 10^{16} W/cm^2. When the laser pulse is in the range of $10\leq I/I_{16}\leq100$, we can obtain the REB energy within the scope of $17.6\leq T$(keV)≤155.

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The energy loss of the incident electron as a result of interaction with the free electron in the plasma may be calculated using Möller's cross section

$$(\frac{d\sigma}{d\varepsilon})^-=\frac{\chi}{E_0}[\frac{1}{\varepsilon^2}+\frac{1}{(1-\varepsilon)^2}+(\frac{\gamma-1}{\gamma})^2\frac{2\gamma-1}{\gamma^2}\frac{1}{\varepsilon(1-\varepsilon)}] \tag{2}$$

where

$$\chi=\frac{2\pi r_0^2 m_e c^2}{\beta^2},\ r_0=\frac{e^2}{m_e c^2}$$

$\beta=v_0/C$ and $\gamma=(1-\beta^2)^{-1/2}$ are the Lorentz parameters of the incident electron, m_e is the rest mass of the electron and v_0 is the speed of the incident electron. The incident electron total energy is $E=\gamma m_e c^2$, the kinetic energy is $E_0=(\gamma-1)m_e c^2$, and ε is the energy transfer in units of E_0. Since the outgoing electron of higher energy is by definition the primary electron, the maximum energy transfer is $\varepsilon_{\max}=1/2$; while in the plasma the minimum energy transfer should be $\varepsilon_{\min}=\frac{1}{2}\frac{\hbar^2\omega_p'^2}{E_0 kT}$, where $\omega_p'=(\frac{4\pi n_p e^2}{m_e\gamma'^3})^{1/2}$ denotes the relativistic modified frequency [12] for the hot plasma, kT is the plasma temperature, γ' is the Lorentz factor of the electron in the plasma and n_p is the plasma density. In the non-relativistic limit, we can see $\varepsilon_{\min}^{1/2}$ is just equal to $\lambdabar_e/\lambda_D$, where $\lambdabar_e$ is the de Broglie wavelength of incident electron and λ_D is the Debye length of the plasma.

Therefore, due to hard collisions the average energy loss per atom of Z free electrons may express as follows

$$ZE_0\int_{\varepsilon_{\min}}^{1/2}\varepsilon(\frac{d\sigma}{d\varepsilon})^{-}d\varepsilon=Z\chi[\ln\frac{1}{4\varepsilon_{\min}}+1-\frac{2\gamma-1}{\gamma^2}\ln 2+\frac{1}{8}(\frac{\gamma-1}{\gamma})^2] \quad (3)$$

Thus, using Eq.(3) we can easily obtain the rate of average energy loss per unit path length x in a medium with n_p atoms per unit volume for the binary collisions

$$-\frac{dE}{dx}=\frac{2\pi n_p Z e^4}{m_e\beta^2 c^2}[\ln\frac{m_e c^2 kT(\gamma-1)}{\hbar^2\omega_p'^2}-\frac{2\gamma-1}{\gamma^2}\ln 2+\frac{1}{8}(\frac{\gamma-1}{\gamma})^2+1-\ln 2] \quad (4)$$

where, $Z=8$ for the Ar atom cluster and n_p is the plasma density.

In addition, to the energy loss due to the binary collisions one must add the contribution from the excitation of the Langmuir collective plasma oscillation

$$-\frac{dE}{dx}=\frac{2\pi n_p Z e^4}{m_e\beta^2 c^2\gamma' 3}\ln[\frac{v_0}{\omega_p'\lambda_D'}(\frac{2}{3})^{1/2}]^2 \quad (5)$$

where $\lambda_D'=[\frac{1}{3}(<v_i^2>_{AV}/\omega_p'^2)]^{1/2}$ is the relativistic modified "Debye length". $<v_i>_{AV}$ is the average speed of the electron in the plasma.

In the following, we calculate the rate of energy loss per unit distance of the REB with 100 keV energy interacting with the Ar clusters at the temperature 0.1-1 keV. The results are shown in Figs. 1(a) and (b). With the increase of the plasma temperature, the energy loss per unit distance caused by collective excitation gradually decreases while that caused by the two-body collisions opposes to it, but the total energy loss almost keeps unchangeable at about 107 MeV/cm. The reason may be as follows: In a dense electron gas, we know that for phenomena involving distances greater than the "Debye length", the system behaves collectively; for distance shorter than this length, it may be treated as a collection of approximately free individual particles. Here, the increase of the plasma temperature, as well as that of the velocity of relativistic electrons, lead to the decrease of the plasma frequency ω_p' and the increase of the "Debye length". Thus,

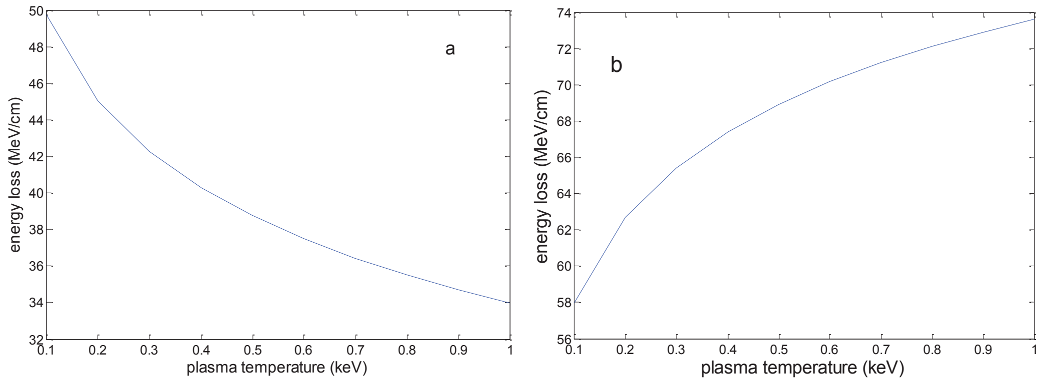

Figure 1: The rate of energy loss per unit distance of the REB with 100 keV energy in Ar atoms at temperature 0.1 keV$\sim$1 keV caused by (a) collective excitation and (b) the two-body collisions.

the increase of the "Debye length" causes the decrease in the number of the electrons participating in the collective oscillation, while the increase of the number of the electrons participating in the random thermal motion. But the homeostasis process in the plasma makes the total energy loss almost unchanged.

2.2 Relevant physics parameters

We take typically the temperature of the Ar plasma being 0.1 keV and electron density of 10^{24}cm^{-3}. For a stopping target, by putting the stopping contributions (4) and (5) together, we may calculate the continuous winded range

$$R=\int\frac{dx}{dE}dE=\frac{(m_ec^2)^2}{4\pi n_pe^4}\int\frac{VdV}{(1-V)^{3/2}}D(V)^{-1} \tag{6}$$

with $V=\beta^2$ and

$$D(V)=\ln\frac{m_ec^2k_BT_e(1/\sqrt{1-V}-1)}{\hbar^2\omega_p'^2}-(2\sqrt{1-V}-1+V)\ln2+\frac{(1-\sqrt{1-V})^2}{8}$$
$$+1-\ln2+\frac{1}{<\gamma>^3}\ln\frac{2c^2V}{3\omega_p'^2\lambda_D'^2}$$

Here, the value of R describes the actual path length of the incident electron during its passage through the plasma. The quasielastic and highly erratic motion for the incident relativistic electrons make them experience multiple-scattering on the target. Such a process is essentially described by the square average deflection per unit path length ($Z=8,\ A=40$)

$$\lambda^{-1}(\mu m^{-1})=8\pi(\frac{e^2}{m_ec^2})^2\frac{Z(Z+1)N_A\rho}{A\beta^4}(1-\beta^2)[\ln(\frac{137\beta}{Z^{1/3}(1-\beta^2)^{1/2}})+\ln1.76-(1+\frac{\beta^2}{4})] \tag{7}$$

where N_A is the Avogadro's number equal to 6.022×10^{23} mole^{-1}, ρ, Z, A are the density, atomic number, and atomic weight the plasma, respectively.

In fact, we really need an efficient packing mechanism to wind the projectile trajectories within a smaller domain in the compressed core. This winding process is easily described by the maximum penetration depth l_0. The simple relationship between the continuous winded range (the stopping range) R and the maximum penetration depth l_0 is given by

$$R=l_0+\frac{1}{2}\frac{l_0^2}{\lambda}+\frac{1}{2}\frac{l_0^3}{\lambda^2} \tag{8}$$

The time that the REB deliver its energy to he plasma is also a very important parameter, a sufficiently short stopping time can be obtained by

$$t_{stop}=\frac{1}{c}\int_{E_{max}/10}^{E_{\max}}\frac{1+E/m_ec^2}{[(E/m_ec^2)(E/m_ec^2+2)]^{1/2}}\frac{dE}{dE/dx} \tag{9}$$

3 Discussion

We obtain the energy loss due to the interactions of REB with a plasma binary electron-electron collisions and the excitation of the Langmuir collective plasma oscillation within the relativistic framework. Taking the Ar clusters having 5×10^4 atoms and the radius of 13.4 nm irradiated by ultraintense ($I\geq10^{16}$ W/cm^2) and ultrafast (duration ~10-100 fs) laser pulses, we calculate the rate of energy loss per unit distance of the REB with 100 keV energy interacting with the Ar clusters at the temperature 0.1 keV. Therefore, the relevant parameters according to the expressions (6), (7), (8) and (9), for 90% energy loss of REB we can obtain $R=40.55$ nm, $l_0=26.57$ nm, $t_{stop}=7.22\times10^{-14}$ sec. The results show that the maximum penetration depth of the REB can match the radius of the cluster, and the REB has enough time deliver its energy to the plasma within a laser pulse. Results can fit the experimental data and well explain the laser energy deposition in the large clusters.

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