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Interaction property between high power laser and cluster medium in the radiation dominant regime

輻射減衰領域における高強度レーザーとクラスター媒質との相互作用特性

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We study the interaction between laser and mediums composed of multi clusters in the intensity regime of $10^{20\text{-}23}$ W/cm^2 based on the two-dimensional particle-in-cell simulation. Assuming cluster mediums with different cluster sizes and a uniform thin foil with the same total mass, we investigate the effect of internal structures of mediums on the interaction dynamics. Dependence of the absorption rate to total surface of the medium is found to change by increasing the laser intensity. Influence of the radiation reaction will be also discussed.

1. Introduction

Recently, intensity of high power short pulse lasers has reached the range of $10^{18\text{-}21}$ W/cm^2. The interaction between such laser fields and matter has opened up various applications such as high energy particle acceleration and generation of intense radiation from tera-heltz to γ-ray [1]. In laser-matter interaction, the state and structure of target material are key ingredients. Among various materials, those composed of multi clusters, which we here refer to as cluster medium, are interested owing to their property of high energy absorption, which can yield efficient ion acceleration, neutron production by nuclear fusion, etc. [2,3]. These studies of laser-cluster interaction have been so far conducted for the linear and electron relativistic regime, i.e., below 10^{20} W/cm^2.

Today, higher intensities of $I = 10^{22\text{-}23}$ W/cm^2, where ion relativistic motion begin to dominate the interaction dynamics, are expected to be achieved [4]. In this regime, new ion acceleration mechanisms such as radiation pressure acceleration for thin foils are expected [5]. In addition, the energy loss of electrons by radiation reaction is considered to be no longer negligible [6]. For clusters, higher intensity lasers can expel more electrons from cluster core, which leads to the Coulomb explosion of clusters with larger radius and then generates more energetic ions [7]. Interaction of cluster mediums in this regime is considered to become different qualitatively from that in the linear and electron relativistic regime, and then, energetic ion acceleration and intense radiation emission can be expected.

In this study, in order to investigate the interaction between laser and cluster medium in the regime $I = 10^{20\text{-}23}$ W/cm^2, we perform numerical simulations using a fully relativistic particle-in-cell code (EPIC3D) [8] that includes radiation reaction in terms of the Landau-Lifshitz equation [9]. Differences of interaction dynamics and energy absorption among cluster mediums with different cluster sizes and solid foil are discussed.

2. Simulation Condition

We assume cluster mediums and a solid foil made from carbon in 2D geometry as shown in Fig. 1. The size of simulation box is L_y = 2048 and L_x that varies from 32 to 128 in normalized unit, which correspond to l_y = 20.48 μm and l_x = 0.32-1.28 μm. The boundary conditions in x and y directions are periodic and outgoing, respectively. A p-polarized laser pulse with the wavelength λ_L = 820 nm excited by the antenna located at L_y = 2 propagates in the y direction. The laser field is uniform in the x direction while having the Gaussian time profile with duration τ = 40 fs (FWHM).

The materials (A)-(D) are assumed to have the same total mass consisting of fully ionized carbon ions (Z = 6) whose density is that of the diamond, $n_{cl}^{(i)} = 1.8 \times 10^{23}$ cm^{-3}. The electron density satisfies $n_{cl}^{(e)} = Z\, n_{cl}^{(i)}$ and $n_{cl}^{(e)} / n_c = 637$, where n_c

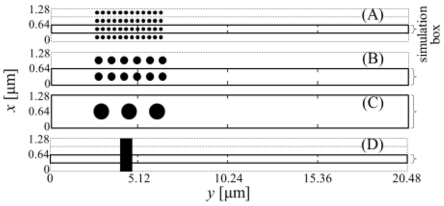


Fig.1. Configurations of the numerical simulation.

is the cutoff density defined by $n_c = m_e \omega_L^2 / (4\pi e^2)$. Clusters in (A)-(C) are modeled by uniform density plasma columns occupying area of radius r_{cl} = (A) 78 nm, (B) 163 nm and (C) 327 nm in the x-y plane. Such clusters are regularly distributed in the region $256 < L_y < 640$. The packing ratio is $f = N_{cl}\, \pi\, r_{cl}^2 / S_a = 0.21$ for all cases (A)-(C), where S_a is the background area occupied by clusters and N_{cl} is the number of clusters in area S_a. Then, the average electron density $n_{av}^{(e)}$ in area S_a is given by $n_{av}^{(e)} / n_c = 130$. We also consider a uniform solid foil (D) of density n_{cl} and thickness $l_{\rm foil}$ = 785 nm.

3. Results and Discussions

Figure 2 shows electric field in the direction of laser polarization, E_x (black), and electron density n_e (red) at $x = l_x / 2$ at time t = 53 fs where $a_0 = 50$ ($I = 5.1 \times 10^{21}$ W/cm^2) and the radiation reaction is not taken into account. Each values for the vertical axis are normalized by E_0, the electric field amplitude corresponding to a_0 = 50, and n_c, respectively. In cases (A)-(C), a part of laser energy penetrates into the medium beyond the initial front surface shown by the dashed line. For small clusters (A) and (B), a large amount of electrons are expelled from the cluster located at the most front side. On the other hand, in case (D), the laser field is reflected with a sharp cut off at the front surface, and an electromagnetic field is excited by electrons pushed by the laser field at the front side to the rear.

The direct interaction between laser field and particles inside of the medium in cases (A)-(C) results in a large energy absorption by particles. Here, in Fig. 3(a), we show the rate of energy absorption $\alpha = (\varepsilon_e + \varepsilon_i) / \varepsilon_{\rm in}$, where ε_e and ε_i are total electron and ion energies and $\varepsilon_{\rm in}$ is the total input energy by the antenna, at final time t = 200 fs for the case of a_0 = 50. The horizontal axis is the total surface S defined by $S = 2\, \pi\, r_{cl}\, N_{cl}$ for (A)-(C) and $S = l_x\, l_{foil}$ for (D). We see that cluster mediums (A)-(C) exhibit higher absorption than the thin foil (D). The higher absorption rate in (B) and (C) than (A) corresponds to the deeper laser penetration into the medium than that for (A) as seen in Fig. 2. In Fig. 3(b), the absorption rate for a_0 = 1 is also given

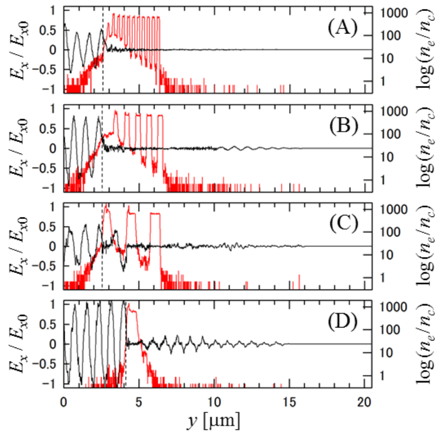
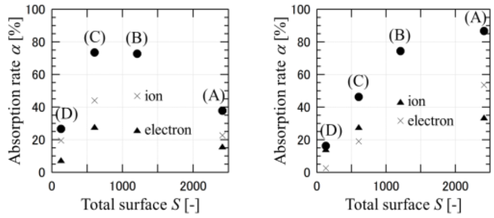


Fig.2. Electric field (black) and electron density (red) at t = 53 fs in the case of a_0 = 50.



(a) a_0 = 50 (b) a_0 = 1

Fig.3. Rate of energy absorption by particles.

for comparison. Interestingly, in the case of a_0 = 1, smaller clusters with larger S exhibit higher α, which is the opposite tendency compared to the case of a_0 = 50. The detail of the difference will be discussed at the conference. In the case of a_0 = 50, we have confirmed that α for cases (A)-(C) decreased by the inclusion of radiation reaction by around 5 %, which is higher compared to that for case (D). This indicates that more energy is converted to radiations in cluster mediums.

Acknowledgments

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