Laser-matter interaction in cluster medium in the radiation dominated regime

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Abstract. We study the interaction between laser and cluster medium in high intensity regime 10^{22-24} W/cm^2 using a particle based integral code (EPIC3D). By introducing four targets consisting of the same mass, i.e. same packing fraction, but having different internal structure, we investigate the effect of cluster on the acceleration dynamics comparing with that of thin film. In the radiation pressure dominated regime, the cluster medium exhibits a higher maximum energy than that achieved by the simple piston mechanism due to the additional accerelation by the Coulomb explosion. The optimum cluster radius for ion acceleration is found to exist depending on the laser power irradiated.

1. Introduction

The interaction between high power laser and matter has opened up various kinds of application such as high energy particle acceleration, generation of intense radiations from tera-heltz to EUV and x-ray, neutron production, etc [1]. Here, the state of material is a key ingredient which determines the characteristics of the interaction, and has to be chosen properly according to the purpose. For instance, besides solid and gas, cluster is interested, which exhibit prominent features in the interaction, i.e., the existence of the linear cluster mode, higher nonlinear absorption and particle acceleration due to the Coulomb explosion [2, 3, 4]. Recently, high energy ion acceleration has been realized in the interaction between a cluster medium and high intensity laser [5]. These phenomena have so far been investigated using laser intensities up to around 10^{21} W/cm^2.

Here, we investigate the interaction between laser and cluster medium extending the intensity higher than 10^{22} W/cm^2 up to 10^{24} W/cm^2. In this regime, ions become relativistic being accerelated by the radiation pressure incorpolating with the Coulomb explosion dynamics. Using a fully-relativistic electromagnetic particle-in-cell (PIC) code (EPIC3D), we study the interaction between laser and targets consisting of the same mass, i.e. same packing fraction, but having different cluster radius, by comparing them with thin film.

2. Simulation condition

In analyzing the laser-cluster interaction in the radiation dominated regime, we carry out a two-dimensional PIC simulation. We employ the periodic and outgoing boundary conditions in x and y directions with the size of $L_x = 128$ and $L_y = 2048$ in normalized unit, which correspond to $l_x = 1.28\ \mu$m and $l_y = 20.48\ \mu$m, respectively. The mesh number in x and y directions are $N_x = 128$ and $N_y = 2048$. A laser pulse with the wavelength $\lambda_L = 820$ nm excited by the antenna located at $y = 0.02\ \mu$m propagates in the y-direction with linear polarization in the x direction. The laser field is uniform in the transverse direction while the Gaussian profile in time with the dulation $\tau = 40$ fs (FWHM) is assumed. Here, we

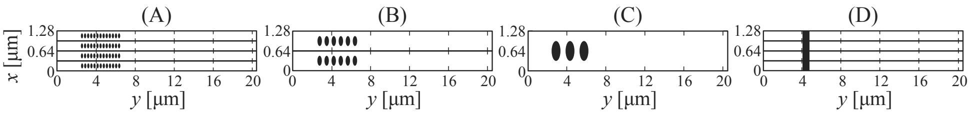

Figure 1. Initial plasma distributions in the EPIC simulation for cases (A) multi cluster medium with cluster radius r_{cl} = 80nm, (B) r_{cl} = 160nm, and (C) r_{cl} = 320nm, and (D) solid thin film.

consider five cases of laser amplitude, i.e., a_0 =50, 200, 400, 600 and 800, where laser intensity ranges from $I = 5.1 \times 10^{21}$W/cm^2 ($a_0 = 50$) to 1.3×10^{24}W/cm^2 ($a_0 = 800$). The corresponding transverse excursion lengths of electron and carbon ion with the charge state $Z = 6$, ξ_e and ξ_i, are found to range from $\xi_e = 6.5\ \mu$m and $\xi_i = 0.3$ nm for $a_0 = 50$ to $\xi_e = 104\ \mu$m and $\xi_i = 4.7$ nm for $a_0 = 800$.

In this study, we introduce three cluster targets consisting of the same mass, i.e. same packing fraction, but having different cluster radius as shown in Figs. 1 (A), (B) and (C). We also consider a solid thin film as shown in Fig. 1 (D) for comparison. Here, we model the cluster by a fully ionized uniform density plasma column occupying an area of radius r_{cl} =80, 160 and 320 nm for cases (A), (B) and (C), respectively, in the x-y plane. The species of the cluster is assumed to be solid carbon ($Z = 6$) whose density is that of the diamond, i.e., $n_{cl}^{(i)} = 1.76 \times 10^{23}$ cm^{-3}. The electron density of the cluster satisfies $n_{cl}^{(e)} = Zn_{cl}^{(i)}$ and $n_{cl}^{(e)}/n_c = 637.4$, where n_c is the cutoff density defined by $n_c \equiv m_e\omega_L^2/(4\pi e^2)$. The skin depth inside of the cluster for fully ionized state is $\delta_e = 5.17$ nm. Such clusters are regularly distributed in the region $2.56 \le y \le 6.40\ \mu$m. The packing fraction defined by $f = N_{cl}\pi r_{cl}^2/S$ is given by $f = 0.21$ for all the cases (A)-(C), where $S = 3.20 \times 3.84\ \mu$m^2 is the area occupied and N_{cl} is the number of clusters in the area S. Then, the average density of electron $n_{av}^{(e)}$ in the area S is given by $n_{av}^{(e)}/n_c = 130.4$ ($n_{av}^{(e)} = 2.16 \times 10^{23}$ cm^{-3}). Hence, the cluster medium is overdense in average if the relativistic effect is not taken into account. In case (D), i.e., the case of thin film, we also assume the same solid carbon plasma with $Z = 6$ that is uniformlly distributed in the region $4.09 \le y \le 4.87\ \mu$m. Here, we set the film thickness $l_{film} = 785$ nm so that the total mass included in the medium is same as that in the cluster medium. The relative relation among the electron and ion excursion lengths, incident laser wavelength, film thickness, cluster radius, and skin depth is given by $\xi_e > \lambda_L > l_{film} > r_{cl} \gg \delta_e \sim \xi_i$ in all the situations considered in this study.

3. Laser-matter interactions in multi cluster medium and solid thin film

First, we investigate the interactions for the cluster medium (B) and thin film (D) in Fig. 1 in the case of two laser intensities, $a_0 = 200$ and 800. The time histories of electron and ion energies, field energy and total energy in the system, and also spatial profiles of electromagnetic field E_x and ion charge density normalized by en_c at $t = 80$ fsec are shown for the cluster medium (B) in the case of $a_0 = 200$ (Figs. 2 (B1) and (B2)) and of $a_0 = 800$ (Figs. 2 (B3) and (B4)), respectively. The corresponding figures for the thin film (D) are shown in Figs. 2 (D1) and (D2) for $a_0 = 200$ and in Figs. 2 (D3) and (D4) for $a_0 = 800$, respectively. The initial density distribution is also shown by dotted line in Figs. 2 (B2) and (B4) where six clusters along the y-axis can be seen while single thin film in Figs. 2 (D2) and (D4). For comparison, the time history of field energy in vacuum and the corresponding spatial profile of E_x at $t = 80$ fsec are shown for $a_0 = 200$ in Figs. 2 (I) and (II), where laser front emitted from antenna reaches to the right-hand side boundary and escape from the system at $t \sim 100$ fsec. At first, we study cases of the thin film (D) and cluster medium (B) for $a_0 = 200$. In the case of thin film (D), after the laser hits the target as seen in Fig. 2 (D1), the electron energy increases initially and ion energy does subsequently. Then, the electron energy saturates and decreases while the ion energy keeps increasing gradually, suggesting that ions are accelerated by the target normal sheath acceleration (TNSA) at the rear surface. This feature can be seen in the ion density distribution in Fig. 2 (D2) at $t = 80$ fsec where the large amount of ions are pushed in the forward direction. As found from the decrease of the total

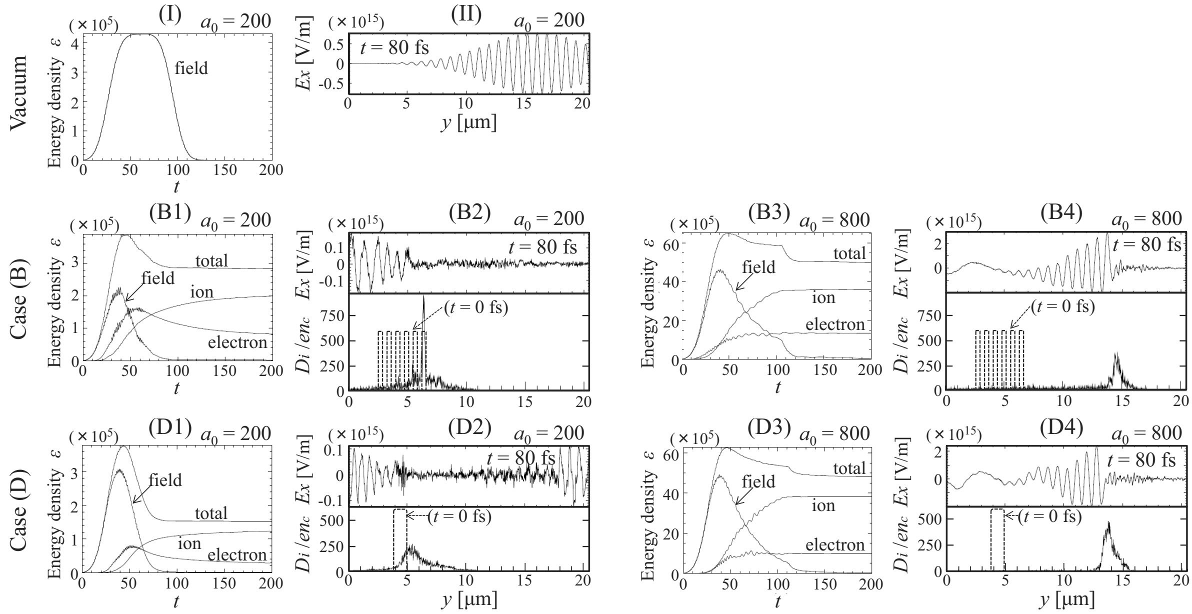

Figure 2. Time history of particles, field and total energies, and spatial profiles of electromagnetic field E_x and normalized ion density at t = 80 fsec for a_0 = 200 and 800 in the cases of vacuum ((I) and (II)), cluster medium (B) ((B1)-(B4)), and thin film (D) ((D1)-(D4)).

energy at $t \sim 45$ fsec from the maximum value, approximately half of the incident laser energy is found to be reflected while partially transmitted due to the relativistic effect as seen in Fig. 2 (D2). On the other hand, in the case of cluster medium (B), the dynamics is qualitatively similar whereas energy partition is found to be significantly different. Firstly, the energy absorption by electron and then the conversion to ion energy reach almost double, which is found from the fact that the decrease of the total energy from the maximum value at $t \sim 45$ fsec is small compared with that observed in Fig. 2 (D1). As seen in Fig. 2 (B2), the initial discrete cluster distributions are disintegrated except that of the most rear side. Here, more ions are found to be pushed not only in forward direction but also backward direction. This is due to the fact that the cluster Coulomb explosion takes place in both directions though forward direction is stronger due to the radiation pressure force.

Next, we consider the same cases (D) and (B) but for a_0 = 800. The case of the thin film is shown in Fig. 2 (D3) and (D4). In this case, after the laser hits the target, electron and ion energy simultaneously increases as seen in Fig. 2 (D3). Interestingly, even after the electron energy saturates, ion energy keeps increasing to a certain level, which is balanced with the decrease of the laser field energy. Namely, it is found that the laser field energy is directly transferred to that of ions. As found in Fig. 2 (D4), this corresponds to the situation that the laser pulse pushes the whole thin film consisting of a bunch of ions, which is referred to as laser piston by radiation pressure. The Doppler shifted long wavelength reflected laser light can also be seen. The ion energy distribution function at t = 200 fsec is shown in (D) in Fig. 3 (II). A quasi-monoenergetic component exhibiting a energy hump around ϵ_i = 9 GeV can be seen. The maximum ion energy, which is approximately 12 GeV, is also indicated in (D) in Fig. 3 (I) together with other laser amplitudes including the case of a_0 = 200 which is around 3 GeV. On the other hand, in the case of the cluster medium (B), the dynamics is qualitatively similar to those in Figs. 2 (D3) and (D4). Namely, initial cluster distribution is disintegrated and pushed forward by the radiation pressure. The ion energy in Fig. 2 (B3) is slightly smaller than that in case (B) whereas the ion bunch is preceded compared with that observed in Fig. 2 (D4) at t = 80 fsec. It is interesting to note in Fig. 3 (II) that the quasi-monoenergetic component locates around 10 GeV which is slightly larger than the case (D) while

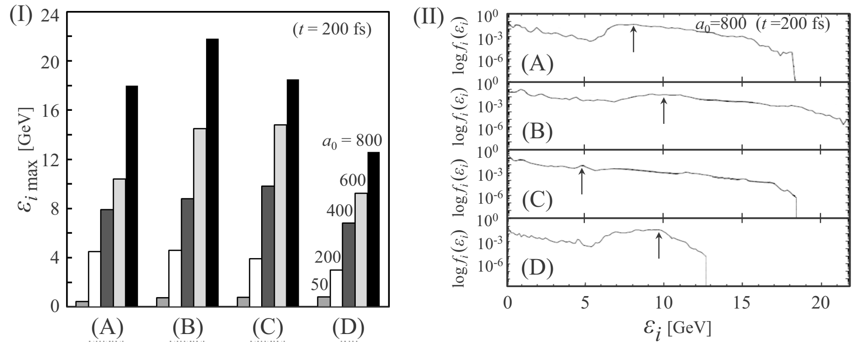

Figure 3. (I) Maximum ion energy obtained in each medium at t = 200 fs for a_0 =50-800. (II) Energy distribution of ions in each medium for a_0 = 800 at t = 200 fs.

the maximum ion energy reaches to approximately 22 GeV. This feature is also shown in (B) in Fig. 3 (I). This is found to result from the acceleration due to the Coulomb explosion of clusters which is added to that of the laser piston.

4. Dependence of ion energy on the internal structure of targets

Here, we summarize the ion energy distribution for a_0 = 800 and the maximum ion energy achieved in the interaction for different laser intensities including the case of (A) r_{cl} = 80 and (C) 320 nm in Fig. 1 in addition to those of r_{cl} = 160 nm and thin film. Note that the energy of the ion bunch due to the laser piston is estimated as (A) 8 GeV, (B) 10 GeV, (C) 5 GeV and (D) 9 GeV per ion. It is found that the maximum ion energy achieved in the cluster media (A), (B) and (C) leads to higher values than that in the solid thin film (D) for for $a_0 \geq 200$. This tendency can be explained from the Coulomb explosion of clusters contained in the medium. To estimate the effect of the Coulomb explosion, here we evaluate the maximum Coulomb potential that can be achieved by single cluster. We assume that all the electrons are excluded from the cluster to infinity and only ions remain with a spatially uniform distribution. In such a case, the potential energy outside of the cluster ($r \geq r_{cl}$) is given by $\phi(r) = 4\pi Zen_i r_{cl}^3/r$ [4, 6]. Then, ions at the cluster surface $r = r_{cl}$ expand to infinity due to the Coulomb repulsion force and gain kinetic energy of $\epsilon_i = Ze\phi(r_{cl})$ which is proportional to r_{cl}^2. Therefore, we can estimate the maximum ion energy as $\epsilon_{i\ \mathbf{max}} = 4\pi Z^2e^2n_ir_{cl}^2$ whose values are obtained for radii (A) 80 nm, (B) 160 nm and (C) 320 nm as 0.24, 0.98 and 3.92 GeV, respectively. In Fig.3 (I), the increases of $\epsilon_{i\ \mathbf{max}}$ in cluster medium compared with the thin film are 0.9-9.0 GeV in the case of a_0 = 800, which are in the same order as the maximum Coulomb potential of cluster calculated in the above. Thus, the large maximum ion energy achieved in the cluster media can be regarded as a result of the Coulomb explosion inside of the media. In other words, the higher internal free energy of the cluster media is used to accelerate the ions to higher energy. It is interesting to note that the relation between the maximum ion energy and cluster radius is different depending on a_0. Namely, in the case of a_0 = 200, medium with smaller cluster radius, e.g. (A) and (B), exhibit larger $\epsilon_{i\mathbf{max}}$ than case (C). In contrast, in the case of a_0 =400 and 600, larger $\epsilon_{i\ \mathbf{max}}$ is achieved in the medium with larger cluster radius. Finally, in the case of a_0 = 800, the case (B) shows the largest $\epsilon_{i\mathbf{max}}$ compared with the other cases. The details will be studied in future work.

5. Conclusion

Based on the PIC simulation, we studied the interaction between laser field in the regime of a_0 = 50-800 and targets consisting of same mass but having different internal structure, i.e., cluster media with different cluster radii and solid thin film. Comparison of ion energies achieved in the interactions with different targets shows the effects of the Coulomb explosion inside of the cluster media. The results indicate that the internal structure, which corresponds to the free energy of the target medium, is important in determining the interaction dynamics and the resulting ion accerelation. In this study, we have not included the radiation damping effect, which will be important in discussing intense radiation emissions from cluster medium. The ion maximum energy shown here is obtained in an ideal one-dimensional situation where transverse expansions of laser field and target are not taken into account. These issues are devoted to future work.

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