Observation of enhanced absorption of laser radiation by nanostructured targets in PIC simulations

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Abstract

It is well known that Brunel’s vacuum heating mechanism is operative for laser energy absorption when the target plasma density rises sharply. For non-relativistic laser intensities and planar targets it is also necessary that the laser should strike the target at oblique incidence. The laser electric field at oblique incidence has a component normal to the surface to extract electrons from the target in the vacuum region for Brunel’s mechanism to be operative. At relativistic laser intensities, oblique incidence is not necessarily required as the $\vec{J} \times \vec{B}$ force is significant and can extract electrons from the target even when the laser is at normal incidence. In this manuscript, the interaction of short and intense laser pulse with structured overdense plasma targets have been studied using 2D particle-in-cell simulations. It is shown that for structured targets the absorption increases many fold. A detailed study and understanding of the absorption process for the structured targets in terms of structure scale length and amplitude have been provided.
I. INTRODUCTION

The production of high energetic charge particles during the interactions between the intense, short pulse laser with overdense plasma and subsequently, its collimated propagation inside the target are important for many applications such as fast ignition scheme of inertial confinement fusion (ICF) [1], generation of energetic charged particle beams [2–4], bright source of X-rays [5, 6], generation of high-order harmonics [7] etc. Therefore, the basic understanding of absorption of laser radiation into overdense plasma and manipulation of the same by controlling the laser and plasma parameters are highly desired. In conventional, intense laser-solid interactions, the laser radiation is absorbed by collisionless processes viz. vacuum heating [8], resonance absorption [9] and $\vec{J} \times \vec{B}$ heating [10] etc. However, for short femtosecond (fs) laser pulses and steep density profile of plasma, the laser radiation is absorbed by vacuum heating and $\vec{J} \times \vec{B}$ mechanism. In the case of vacuum heating, a p-polarized laser obliquely incident on a plasma surface has an electric field component normal to plasma surface. This normal component of electric field pulls the electrons into the vacuum during one-half of the laser cycle and then returns them back into the target with a quiver velocity in next half laser cycle. However, at normal incidence, vacuum heating would be absent as there would be no component of the electric field vector normal to the plasma surface. The absorption process will then take place solely through $\vec{J} \times \vec{B}$ mechanism which is typically small when the laser intensity is small so as to have electron quiver velocity in the electromagnetic field of the laser radiation non-relativistic.

Recently, there have been a lot of experimentations with structured targets [11, 15]. There have also been indications that the laser absorption improves when structured targets are employed [12–15]. We explore this question with the help of Particle - In - Cell (PIC) studies in the present manuscript. We treat the structured target as a given profile for plasma density in our simulations. The premise for this is based on the fact that the laser intensity at the front will inevitably ionize the target. However, in the case of a short pulse, the ionized plasma medium will not have a sufficient time to expand before it encounters the main region of the pulse. Thus the structure of the target will be embedded in the density profile of the preformed plasma.

For our numerical study, we will, therefore, consider the interaction of the main laser pulse with both planar plasma density targets and those having a specified structure. The
simulations clearly show that for structured targets the laser absorption gets significantly enhanced leading to the heating of the electrons. A detailed study is carried out which illustrates that Brunel mechanism is operative in a novel fashion for the structured targets wherein the electrons get extracted in the vacuum region from a larger area when the target is structured.

We have organized this paper as follows. In Section II, we describe the simulation set-up for the PIC simulations. In section III simulation results are presented which show the enhancement in absorption and the significant increase in the heating of the electrons. In section IV the dependence of absorption on structure scale length has been provided. Finally, we conclude our findings in section V.

II. SIMULATIONS SET-UP

For our simulation, a Gaussian laser beam with FWHM of 3µm with a top hat temporal profile of 30 femtoseconds (fs) enters from the left boundary and interacts with a 2-D plasma slab. The laser is chosen to be p-polarized with its electric field in the Y-direction and the magnetic field in the ”-ve” X-direction as shown in Fig. 1. The laser propagates in the Z-direction and interacts with plasma slab at normal incidence. The size of plasma slab is taken as 6λ in the transverse direction ẑ and 9λ in the longitudinal direction ẑ of the propagation direction of laser light (where λ = 1µm is laser wavelength). There is a vacuum region of 2λ in front of plasma slab and 1λ at the rear of the plasma slab. The absorbing boundary conditions have been used for the electromagnetic fields and reflecting boundary conditions have been used for particles. We have used both planar target with the uniform plasma density of 10n_c (where n_c is the critical plasma density for laser) as well a plasma slab with a ripple in its density chosen to be of the form of \( n_0(y) = n_0 e^{\frac{y}{l_s}} \) where \( l_s = \frac{2\pi}{k_s} \) represents density scale length associated with the density inhomogeneity having an amplitude of \( \varepsilon \). The schematic of simulation set-up for both planar as well as inhomogeneous structured target has been shown in Fig. II(a) and in Fig. II(b) respectively. The mesh size is chosen to be \( \delta z = \delta y = 0.02 c/\omega_p \). This resolves the scale length of density inhomogeneity appropriately. Furthermore, \( \omega_p = \sqrt{4\pi n_0 e^2/m_e} \) is plasma frequency and \( c/\omega_p = 5 \times 10^{-6} cm \) is electron skin depth. The ions, having charge and mass of the proton, are kept at rest during simulation.
III. LASER ABSORPTION

We consider the case of a low intensity ($10^{13} W/cm^2$) laser incident on both planar homogeneous and inhomogeneous plasma target. The plasma density rise for both these cases is steep (compared to the laser wavelength). For the choice of a Gaussian laser profile, the laser intensity varies along the transverse direction. The ponderomotive force felt by the electrons are thus different at the different transverse locations of the target surface. In the central region due to higher laser intensity, the electrons should get pushed out towards lower intensity. The depletion of electrons from high-intensity region should form a cavity. The formation of such cavity can be clearly seen for relativistic intensities of $I=10^{19} W/cm^2$ that we have considered in our studies here in Fig. 2(b) (which is a zoomed image of Fig. 2(a)) at time $t = 33.70$ fs for the homogeneous target. The same structure gets formed for the inhomogeneous target which has been observed Fig. 3. Thus a transverse dimple in the plasma electron density profile automatically also gets created. However, such a "caving in" of electron density is very small compared to the laser wavelength. The effect of this small structure formation is negligible on absorption properties which are the issue of main concern here.

We now consider the absorption studies for the case when the laser intensity is weak $10^{13} W/cm^2$. For the planar homogeneous target, we expect that the vacuum heating would be inoperative as the electric field vector of the laser (which is incident normal to the target) is parallel to the surface. The intensity of $10^{13} W/cm^2$ is weak and electrons remain non-relativistic. Therefore, the $\vec{J} \times \vec{B}$ mechanism is insignificant for this case. This is indeed observed as can be seen from Fig. 4 where we have plotted total kinetic energy of the electrons as a function of time. For the same laser intensity and all other conditions when the target is taken to be inhomogeneous the total kinetic energy of electrons registers a significant growth with time as witnessed from the dashed green line of the same Fig. 4. We also denoted the electron number distribution (on a color log scale) as the function of $p_y$ and $p_z$ at $t = 24.15$ fs in Fig. 5 for the both planar homogeneous and structured target cases and we also draw the energy circles (with yellow color) on $p_y - p_z$ plane. For planar homogeneous target, in Fig. 5(a) we see that the spread of electron number distribution is very low and even do not cross the energy circle of 28 eV. However, for structured inhomogeneous target the momenta spread of electron is around 700 eV (see Fig. 5(b)) which is comparatively much
higher than homogeneous. Thus it is clearly evident that the laser radiation absorption is considerably better for the structured target.

We have repeated the study at higher relativistic intensity of the laser (viz. $I = 10^{19} W/cm^2$). In this case, even for the homogeneous target there is a significant increase in the electron energy. However, for the structured case the acquired energy is still considerably higher. This is evident from Fig. 4 which shows the growth of the total electron kinetic energy as well as from the plots of Fig. 6(c) and (d) which show the momenta spread in the $p_y$ vs. $p_z$ plane. In Fig. 6, the time evolution of the electron number distribution as function of momenta for both homogeneous as well as inhomogeneous structured target is shown. For homogeneous planar target, we see from Fig. 6(a) and (b) that electron number distribution at time $t = 16.65$ fs have maximum energy around 17.5 KeV and at later time $t = 24.15$ fs, few electrons have energy around 230 KeV with narrow spread. However, in the case of inhomogeneous structured target, at time $t = 16.65$ fs the electrons have more energy around 66 KeV as well as more spread (see Fig. 6(c)) compared to planar homogeneous target. Furthermore, at later time $t = 24.15$ fs, the most of the electrons have energy around 230 KeV (see Fig. 6(d)) which indicates that laser absorption is more in structured target.

The understanding of the enhanced absorption can be understood from the schematic cartoon plots of Fig. 7. When a laser is normally incident on a homogeneous target there is no component of electric field which can drag the electrons out in the vacuum as shown in Fig. 7(a). However, when the surface is corrugated as shown in Fig. 7(b) even at normal incidence the electric field component $E_y$ can drag the electrons out in the vacuum like low density region from the high plasma density region. Furthermore, the laser fields in this case also access an increased surface area. It is now of interest to know how does the absorption depend on the inhomogeneity scale length and the inhomogeneity amplitude (which defines the density disparity). The next section provides the details of this study.

IV. DEPENDENCE OF ABSORPTION ON STRUCTURE PARAMETERS

We have considered various inhomogeneity scale lengths and amplitude of the plasma density profile and studied the total kinetic energy acquired by the electrons as a function of time. This has been shown in Fig. 8. This figure clearly shows that the total kinetic energy of electrons is largest only for an intermediate value of $(k_s = 0.5 \pi, l_s = 4c/\omega_p)$ of
the inhomogeneity scale length. Both increasing and/or decreasing the inhomogeneity scale length results in reduced absorption. This can be understood by realizing that for the laser intensity $I = 1 \times 10^{19} W/cm^2$ considered for this study, the distance by which the electrons can be dragged out along the $y$-direction $y_{osc} = c E_L/\gamma m_e \omega_L^2$ in one laser cycle is also about $4c/\omega_p$ where $E_L$ and $\omega_L$ are laser electric field and laser frequency respectively. Thus, when the inhomogeneity scale length is much sharper than $y_{osc}$ the dragged electron would enter another high density region on the other side in one laser cycle as the spacing between intervening high and low densities are very small. The electrons thus would not experience the vacuum like region important for the Brunel mechanism to be operative. When the inhomogeneity scale length is much broader than the $y_{osc}$, even then the electrons will not experience the vacuum region. Thus the optimum scale length is when $y_{osc}$ is comparable with the inhomogeneity scale length.

It should also be noted from Fig. 8 that there is an amplitude dependence also in the absorption rate. A high amplitude of inhomogeneity seems to do better for absorption as the contrast between low and high density region is better for this case.

V. SUMMARY AND DISCUSSION

We have carried out the 2D PIC simulations of the short pulse intense laser interaction with the rippled pre-ionized plasma target. It is shown that the laser absorption is better for structured targets for both relativistic as well as non-relativistic laser intensities. It is shown that this happens as a result of providing increased surface area for the Brunel’s mechanism of vacuum heating. Furthermore, even at normal incidence, there is no component of electric field normal to the surface to drag the electrons out in the vacuum region for a normal homogeneous target. The structured target, on the other hand, provides a geometry for the electric field to be normal to the imposed inhomogeneity. Thus, the electrons can be dragged out from high to low density regions for a vacuum heating like mechanism to be operative.

There have been experiments [15] which have reported increased propagation distance of energetic electron beams generated by lasers in nano structured targets. The explanation for the phenomena has been provided on the basis of suppression of Weibel instability by the structured target which aids the unhindered propagation of the electrons in the medium. It appears that in such experiments the enhanced generation of energetic electrons can also
play an additional role in aiding the propagation over long distance.

It is interesting to note that the structured targets play important roles both in enhanced generation of energetic electrons as well as aiding its propagation through plasma medium over long distances by suppressing Weibel like instabilities which would otherwise be greatly detrimental.

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[1] M. Tabak, D. S. Clark, S. P. Hatchett, M. H. Key, B. F. Lasinski, R. A. Snavely, S. C. Wilks, R. P. J. Town, R. Stephens, E. M. Campbell, R. Kodama, K. Mima, K. A. Tanaka, S. Atzeni, and R. Freeman. *Physics of Plasmas* **12**, 057305 (2005).

[2] R. B. Stephens, R. A. Snavely, Y. Aglitskiy, F. Amiranoff, C. Andersen, D. Batani, S. D. Baton, T. Cowan, R. R. Freeman, T. Hall, S. P. Hatchett, J. M. Hill, M. H. Key, J. A. King, J. A. Koch, M. Koenig, A. J. MacKinnon, K. L. Lancaster, E. Martinolli, P. Norreys, E. Perelli-Cippo, M. Rabec Le Glaohec, C. Rousseaux, J. J. Santos, and F. Scianitti. *Phys. Rev. E* **69**, 066414 (2004).

[3] S. Kar, A. P. L. Robinson, D. C. Carroll, O. Lundh, K. Markey, P. McKenna, P. Morreys, and M. Zepf. *Phys. Rev. Lett.* **102**, 055001 (2009).

[4] J. Fuchs, P. Antici, E. DHumires, E. Lefebvre, M. Borghesi, E. Brambrink, C. A. Cecchetti, M. Kaluza, V. Malka, M. Manclossi, S. Meyroneinc, P. Mora, J. Schreiber, T. Toncian, and H. Ppin. *Nat. Phys.* **2**, 48 (2006).

[5] A. Rousse, C. Rischel, and J.-C. Gauthier. *Rev. Mod. Phys.* **73**, 17 (2001).

[6] L. M. Chen, F. Liu, W. M. Wang, M. Kando, J. Y. Mao, L. Zhang, J. L. Ma, Y. T. Li, S. V. Balanov, T. Tajima, T. Kato, Z. M. Sheng, Z. Y. Wei, and J. Zhang. *Phys. Rev. Lett.* **104**, 215004 (2010).

[7] U. Teubner and P. Gibbon. *Rev. Mod. Phys.* **81**, 445 (2009).

[8] F. Brunel. *Phys. Rev. Lett.* **59**, 52 (1987).

[9] S. C. Wilks, W. L. Kruer, M. Tabak, and A. B. Langdon. *Phys. Rev. Lett.* **69**, 1383(1992).

[10] W. L. Kruer and Kent Estabrook. *Phys. Fluids* **28**, 1(1985).

[11] Michael A. Purvis, Vyacheslav N. Shlyaptsev, Reed Hollinger, Clayton Bargsten, Alexander Pukhov, Amy Prieto, Yong Wang, Bradley M. Luther, Liang Yin, Shoujun Wang and Jorge J. Rocca. *Nature Photonics* **7**, 796(2013).

[12] M Bianco, M T Flores-Arias, C Ruiz and M Vranic. *New J. Phys.* **19**, 033004 (2017).

[13] M. Raynaud, J. Kupersztych, C. Riconda, J. C. Adam, and A. Hron. *Physics of Plasmas* **14**, 092702 (2007).

[14] Clayton Bargsten, Reed Hollinger, Maria Gabriela Capeluto, Vural Kaymak, Alexander Pukhov, Shoujun Wang, Alex Rockwood, Yong Wang, David Keiss, Riccardo Tommasini,
Richard London, Jaebum Park, Michel Busquet, Marcel Klapisch, Vyacheslav N. Shlyaptsev, Jorge J. Rocca, *Science Advances* **3**, e1601558 (2017).

[15] Gourab Chatterjee, Prashant Kumar Singh, Saima Ahmed, A. P. L. Robinson, Amit D. Lad, Sudipta Mondal, V. Narayanan, Iti Srivastava, Nikhil Koratkar, John Pasley, A. K. Sood, and G. Ravindra Kumar. *Phys. Rev. Lett.* **108**, 235005 (2012).
FIG. 1. The schematic of simulation set-up for a p-polarized laser-plasma interactions at normal incidence: electric field of laser is in Y-direction, magnetic field of laser is in "-ve" X-direction, and propagation vector is in Z-direction (a) Planar uniform plasma target (b) Inhomogeneous structured target
FIG. 2. (a) The electron density [in unit of $n_0$] for case of planar target at time $t = 33.70$ fs for intensity $I = 1 \times 10^{19} W/cm^2$: (b) Zoomed image of (a) where we can see the formation of the cavity due to evacuation of electrons from high-intensity region to low-intensity region (highlighted by arrow)
FIG. 3. The electron density [in unit of $n_0$] for structured inhomogeneous target ($\varepsilon = 0.5$, $k_s = \pi$) at time $t = 33.70$ fs for intensity $I = 1 \times 10^{19} W/cm^2$: the formation of cavity similar to planar homogeneous target can be seen.
FIG. 4. Total kinetic energy of electrons [in unit of $n_0 m_e c^2$] for various parameters of ripple for intensity $I = 1 \times 10^{13} W/cm^2$ and $I = 1 \times 10^{19} W/cm^2$.
FIG. 5. The $p_zp_y$ [in unit of $m_ec$] phase space of electrons for laser intensity $I = 1 \times 10^{13} W/cm^2$ at time $t = 24.15$ fs, the circles (yellow color) represent the energy curve with 28 eV and 700 eV respectively: (a) In uniform target case, momenta is confined within circle (b) In structured target ($\varepsilon = 0.5$, $k_s = 0.5\pi$), the momenta spread as well as energy is higher which confirms that the structured target is comparatively better for laser absorption.
FIG. 6. The $p_zp_y$ [in unit of $m_e c$] phase space of electrons for laser intensity $I = 1 \times 10^{19} \text{W/cm}^2$, the circles (yellow color) represent the energy curve with 17.5, 66 and 230 KeV respectively: (a) & (b) The momentum at time $t = 16.65$ and $t = 24.15$ fs respectively for uniform target case where collimation in momenta can be seen (c) & (d) In structured target ($\varepsilon = 0.5$, $k_s = 0.5\pi$), the momenta spread as well as energy is higher which confirms that the structured target is comparatively better for laser absorption.
FIG. 7. Sketch of vacuum heating mechanism (a) In normal incidence for homogeneous planar target, there is no electric field normal to plasma surface. Therefore, there is no vacuum heating (Brunel’s mechanism). (b) However, for structured nano-wire target, in normal incidence case, there is electric field normal to side plasma surface which satisfies the vacuum heating condition and increases the absorption of laser radiation compare to conventional vacuum heating (Brunel’s mechanism).
FIG. 8. Total kinetic energy of electrons [in unit of $n_0 m_e c^2$] for various parameters of ripple for intensity $I = 1 \times 10^{19} W/cm^2$. 