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Particle Simulations of High-Intensity Laser Interaction with Cone Targets

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Abstract. Hollow cone-shaped overdense plasma targets were used to investigate the generation and transport of fast particles in a high-intensity laser-matter interaction. Using 2d PIC simulations we examine cone, cone-wire and cone with an open tip target designs. Localization of electron jets and an angular spread are found in all cases of the laser-cone interaction. However, in the cone-wire geometry, at later times, the charge separation and radial electric fields around the wire collimate electron streams with an electron hot spot at the front end of the wire. The main mechanism of the electron transport in the targets is the reflection of electrons from the potential walls of the cone surface, and no significant surface electron transport is observed. Furthermore, the presence of harmonics in the reflected light suggests that the field intensity in the cone can be enhanced not only by simple multiple reflection but also by the field modulation due to harmonics generation. Moreover, it is found that the laser interaction with the open-tip cone can efficiently generate trains of short ($<\lambda$) attosecond electron sheets close to the laser axis.

1. Introduction

The generation of fast particles in a high-intensity laser-solid interaction is a hot research topic with huge potential for a large number of applications. The quality of the particle beams, their energy spectrum, collimation and guiding are some of critical issues in this field and significant research efforts are focused on modeling and understanding the interaction for various laser-target conditions and configurations that range from thin foils, wires and hemispherical shells to sophisticated cone-shaped targets particularly relevant to the fast ignition (FI) schemes for IFE [1]. The idea to use a hollow cone in FI is stimulated by the fact that the ignition pulse can experience significant energy losses during its propagation through the plasma corona. In order to clear the path of the ignition pulse and to allow generation of fast electrons closer to the core, a re-entrant gold cone inserted into the shell has been introduced into FI concept with some promising results [1]. It has been suggested by numerical simulations that the hollow cone can efficiently guide the laser light and fast electrons towards the tip of the cone and thus, to increase the laser intensity and hot electron density [2-3]. However, the complex physical picture of the interaction is not yet fully understood.

In order to explore the laser-cone interaction and application potential (FI, particle acceleration and guiding, harmonics generation and attosecond electron bunches, etc.), we investigate here intense laser interaction with hollow cone-shaped solid targets.

2. Simulation results and discussion

To investigate particle acceleration and transport in a laser-cone interaction, 2d relativistic EM PIC simulations with absorbing boundaries were carried out. An intense linearly polarized (along *y*-axis) Gaussian laser beam was launched from the left of the simulation box in *x*-direction and focused onto a focal spot inside the cone shaped plasma targets. The laser strengths were a_0 = 0.7-2 (for the laser wavelength λ = 1μm the intensity is $I \approx 0.7\text{-}5.5\times10^{18}$ W/cm^2), the diameter of the focal spot was 12λ, and the plasma densities were n =10-20$n_{\rm cr}$ ($n_{\rm cr}$ is the critical density). In the simulations the number of grid cells was 40/λ with 50 particles/cell, initial electron temperature was set to 2-5keV, and in most simulation runs ions were immobile.

We put an emphasis on the following target designs: cone, cone with an attached wire, and cone with an open tip. The wall thickness of the hollow cones was 6.25λ, and the cone open angle was $\alpha = 60^\circ$. The diameter and length of the wire were 5λ and 24λ, respectively, and the diameter of the hole in the open-tip cone case was 6λ. In the simulations the time t/T = 0 (T is the laser period) was set to the peak intensity of the laser beam at the focal spot with the center at (x/λ, y/λ) = (0, 0). In Fig. 1 we show scatter plots of the fast electrons E > 3MeV in space for the specified cone targets at t/T = 57. The plasma density is n =10$n_{\rm cr}$, the laser pulse has rising time $t_{\rm r}$ = 5T and after the laser strength is constant at a_0 = 2. It is found that in the cone (Fig. 1a), and cone-wire (Fig. 1b) cases an efficient heating of the target (including the wire) is achieved. Although the deposition of the laser energy into the open-tip cone (Fig. 1c) is much lower, we note that this case is the most efficient from the point of view of generation of ultra relativistic electrons that can travel far from the target. Furthermore, for the cone target (Fig. 1a) a large number of energetic electrons is concentrated in the vacuum region around the cone while, for example, in the cone-wire case at this time there is a significant stream of forward propagating electrons. The reason for this difference lies in the fact that the attached wire serves as an additional source of cold electrons that can provide return currents. From Fig. 1 we see that in all cases the generation of fast electrons is followed by an angular spreading of the fast beams.

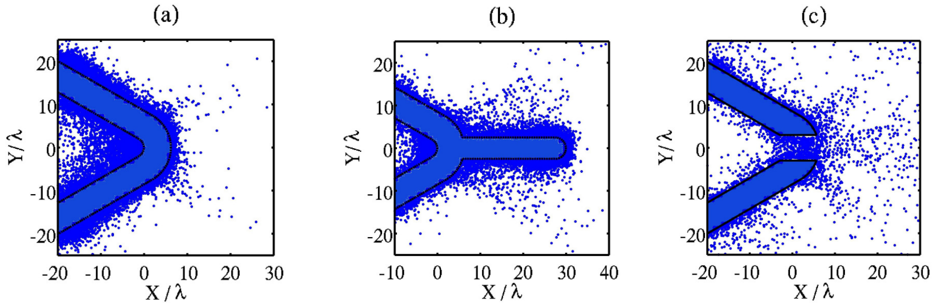

Figure 1. Scatter plots of the fast electrons E > 3MeV in space for (a) cone, (b) cone-wire and (c) open-tip cone targets at t/T = 57. The laser beam a_0 = 2 is launched from the left-hand boundary onto 12λ focal spot inside the cone with the center at (0, 0). The plasma density is n = 10$n_{\rm cr}$, and the laser wave has rising time $t_{\rm r}$ = 5T and after that the intensity is constant.

In Fig. 2 we show directions of the fast electrons E > 1.5MeV in space at t/T = 4.7 (Fig. 2a), typical electron trajectories (Fig. 2b), and generated quasi-static magnetic fields cB_z (in laser strength units) in space (Fig. 2c) for the cone target n =10$n_{\rm cr}$. Here, the laser pulse has Gaussian temporal profile with the rise and fall time of $t_{\rm r} = t_{\rm f}$ = 36T, and a_0 = 0.7 at the peak. The formation of the “star” structure (an angular distribution) of the fast electrons shown in (Fig. 2a), indicate a complex interaction of the plasma surface with the field which is a superposition of incident laser and (multiple) reflected light from the cone walls. Some fast electrons have enough energy to travel far from the cone (see Fig. 2b: electrons with maximum energies 1.2MeV and 0.8MeV), however the dominant motion of the electrons after the interaction with the laser wave (see Fig. 2b: trajectory 0.8MeV) is bouncing between the cone walls due to the charge separation. These electrons contribute to the strong forward and return currents which result in generation of quasistatic magnetic fields (here ~ 15MG), Weibel instability and formation of magnetic filaments with directions close to the surface normal (Fig. 2c). In separate simulation runs (not shown), with the same laser-plasma parameters as in Fig. 2, but using an oblique foil at 45° with mobile ions, it has been found that the reflection from the walls and drift of the fast electrons in the laser wave direction play an important role in energy transport well beyond the laser-plasma interaction region (in the case of a cone that would be transport of energy from the side-walls to the tip). Moreover, it has been found that these electrons are responsible for proton acceleration beyond the focal spot and creation of low-energy proton wings.

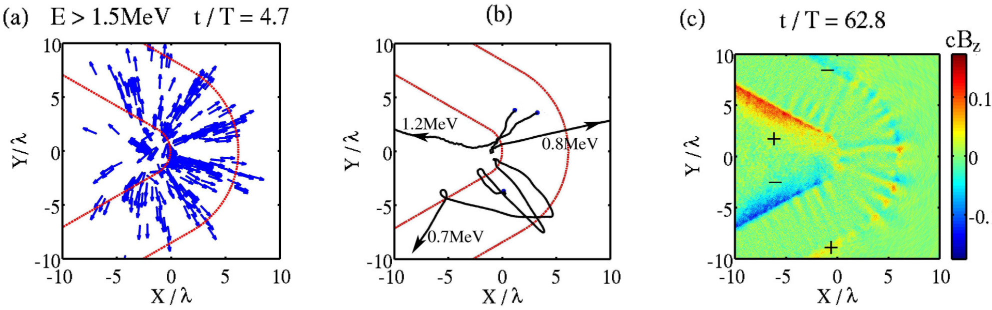

Figure 2. (a) Directions of the fast electrons E > 1.5MeV at t/T = 4.7, (b) electron trajectories and (c) magnetic field cB_z in space for the cone target with the plasma density n = $10n_{cr}$. The laser wave has Gaussian time profile with the rising time t_r = $36T$ and with the peak at a_0 = 0.7.

It has been found that the cone-wire target can generate more hot electrons with a smaller divergence of the beam [1]. Although it appears from Fig. 1a-b that both, the cone and cone-wire have similar divergence of the electrons, the following mechanism plays the crucial role in collimation of the electrons in the cone-wire geometry at later times. We illustrate the mechanism in Fig. 3a-b, where we plot test electron trajectories (Fig. 3a), and their energy history (Fig. 3b). After some very energetic electrons, which can travel with a large angle with respect to the laser propagation axis, leave the cone-wire target (Fig. 3a-b: curves 1 and 3), the established ES field around the target surface strongly affects the subsequent electron dynamics. Since the electric field around the wire is in radial direction, it has a collimation effect on forward propagating electrons (see in Fig. 3a-b: curve 2). Moreover, it is found that the tip of the wire serves as a collector of energetic electrons becoming a hot spot with generated strong quasistatic magnetic fields. Accumulated electrons then oscillate along the wire in backward direction (Fig. 3a-b: curve 2).

In Fig. 3c we show a window snapshot (an interaction region is included) of the magnetic field cB_z inside the cone at t/T = 4.7. The solid line is n = $0.5n_{cr}$ density contour (below the contour is the dense cone plasma), while the black arrows are directions of the fast electrons E > 1.5MeV. As we can see, there are bunches of energetic electrons formed in each laser cycle. Some bunches are ejected into the vacuum region inside the cone while some are directed along the plasma surface. Although it has been suggested [2-3], that self-generated magnetic fields transport the electrons along the target surface, the directions of the fast surface electrons seen in Fig. 3c are instantaneous, i.e. these electrons are a part of the wave-plasma dynamics inside the wave cycle. In fact, in our simulations it has been found that a very small fraction of electrons is accelerated along the surface. The dominant acceleration here is vacuum and $j \times B$ heating (in Fig. 3c electrons below the density contour). The intensity of the EM fields inside the cone can easily exceed the incident field value due to the multiple reflection of the laser light. Moreover, we note that during reflections of the light from the cone walls, the light is modulated (appearance of sharp spikes in the field intensity) due to generation of high harmonics. In Fig. 4a we show harmonic spectrum of the reflected light, that differs from spectra obtained from single interaction of p- or s –polarized laser light with solid targets.

The spread of the fast electrons in the open-cone can be very pronounced, however in this case the most energetic E > 10MeV electrons are recorded far from the target (Fig. 4b-c), promising an attractive tool for generation of attosecond electron bunches. Two electron beams E > 5MeV are observed close to the laser axis with a short (few λ) high energetic E > 10MeV part at the front of the beams. Moreover, it is found that the beams consist of trains, shifted by $\lambda/2$ (see Fig, 4c), of well defined thin (< λ) mono-energetic electron sheets separated in space by λ [4].

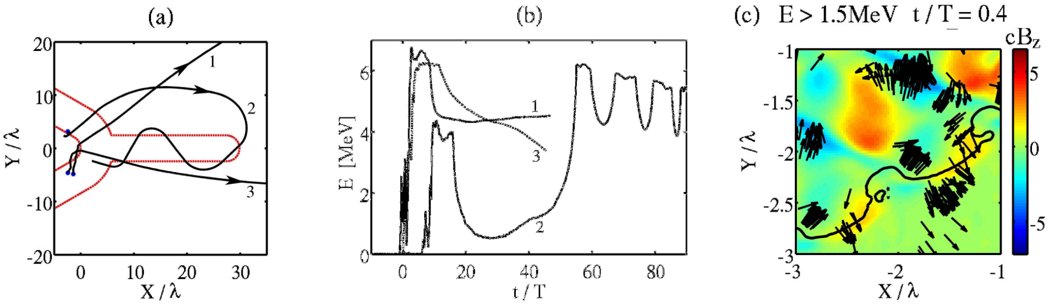

Figure 3. (a) Trajectories of the fast test electrons in space and (b) their energy in time for the cone–wire target. (c) Snapshot of the magnetic field cB_z (a window from inside the cone), directions of the fast electrons E > 1.5MeV (arrows), and the density contour $n = 0.5n_{cr}$ (solid line) at $t/T = 0.4$. The parameters of the simulations were the same as in Fig. 1.

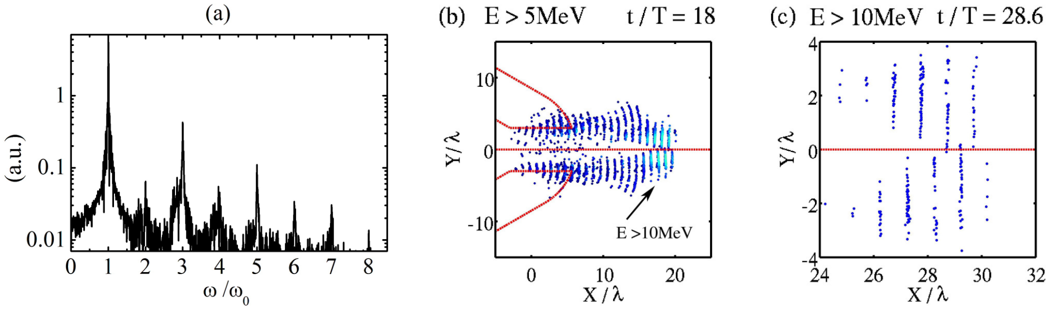

Figure 4. (a) Harmonics of the reflected light from the cone target. (b) Fast electron bunches in space for E > 5MeV and t/T = 18, and (c) close view at the train of electrons with E > 10MeV at t/T = 28.6. The parameters of the simulations are the same as in Fig. 1.

3. Summary

Simulation analysis reveals that hollow cone-shaped plasma targets discussed here, exhibit an angular spread of the fast electron jets. Due to the guiding and collimation of the forward propagating electrons in the cone wire-geometry, the tip of the wire becomes a collector of the electrons and a hot spot with intense quasistatic magnetic fields. Furthermore, no significant fast surface electrons are found which suggests the need for further target optimization. The results indicate that the field intensity in the cone is enhanced by harmonic generation, as well. Moreover, it is found that the strong laser interaction with an open-tip cone can efficiently generate attosecond electron sheets.

Acknowledgments

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