Focusing of relativistic electron beams by a solid cone

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Abstract. A scheme for focusing relativistic electron beams has been proposed by use of a solid cone based upon two dimensional particle-in-cell simulations. We compare the transport of hot electrons, produced during the interaction of ultra-intense laser pulse with the targets, through the cone shape target and a flat target. It is found that relativistic electrons can be confined and focused effectively in the cone target case, where both the electron density and temperature have been increased more significantly than the flat target case.

1. INTRODUCTION
In recent years, relativistic electrons generated during ultra-intense laser pulse interaction with solid targets have been extensively studied [1]. Many kinds of acceleration mechanism have been found, such as resonant absorption [2], vacuum heating [3], $J \times B$ heating [4] and so on. Most of these studies are focused on laser absorption and hot electron generation. However, for many applications usually relativistic electron generation is not the whole story. In fact, the transportation of hot electrons also plays a critical role. In the fast ignition scheme for the inertial fusion [5], the ignition laser pulse firstly interacts with an plasma channel where the laser energy transfers into the relativistic electron beams. Afterwards these hot electrons transport into the overdense plasma, where the laser pulse can not propagate, and deposit their energy in the D-T pellet to ignite it. In this scheme the efficiency of transportation of the hot electrons from the critical density to the target center is a crucial issue. Usually the energy of the hot electrons should be about 1MeV, the current be 100–1000MA, and the radius of the electron beam be at 100$\mu$m. For the transport of such large current relativistic electron beams in the overdense plasma, they can be scattered away easily and meanwhile evolve into many filaments due to some instabilities. On the other hand, electrons accelerated during the laser interaction with solid targets usually have a large spreading angle. All these problems and/or disadvantages have to be solved.

Lots of efforts have already been done to resolve these problems [6]. In 2001, by use of a hollow cone Kodama et al. could be able to produce increased neutron yields significantly [7]. Sentoku et al. found from their simulations for this experiment that not only the laser pulse but also some of the hot electrons have been focused to the tip of the cone [8]. Recently, Li et al. have confirmed this electron focusing mechanism in their experiments by use of a flat target [9]. Therefore both the laser and electron focusing are responsible for the neutron production increase. Campbell et al. have suggested ways to control relativistic electron beams by radially layering vacuum gaps and/or dissimilar materials with varying ionizability [10]. They found a negative radial gradient in the plasma density.
can produce confining fields that can, in principle, confine the hot electron column to nearly the laser injection spot size.

In this paper, we propose a scheme for micro-focusing of relativistic electron beams by use of a solid cone target. The relativistic electron beams are produced by ultra-intense laser pulse radiated onto a solid surface. When these hot electrons are ejected into the overdense plasma target in a cone shape, they are focused.

2. SIMULATION RESULTS AND DISCUSSIONS

We have performed two-dimensional particle-in-cell (2D PIC) simulations. For comparison, we have taken two simulations with the same laser and plasma parameters except the target profile as shown in Figs. 1(a) and 1(b). In the target, plasma is homogeneous in the region $21\lambda \leq X \leq 66\lambda$, the density is $6n_{cr}$, where $n_{cr} = m_e \omega_p^2 / 4 \pi e^2$ is the critical density, corresponding to $1.1 \times 10^{21} / cm^3$ for the laser wavelength $\lambda = 1 \mu m$. At the left vacuum-plasma interface there is an exponential decreasing transition region from $X = 21\lambda$ to $X = 19\lambda$ with the scale length $2 \mu m$. The plasma consists of electrons and ions (the ion mass is $3600m_e$), and the initial electron and ion temperatures are 5 keV and 0.1 keV, respectively. The p-polarized laser pulse normally irradiates the target from the left side of the simulation box. The focal spot diameter is $20 \mu m$ with a Gaussian profile. The temporal profile of the laser pulse is $a = a_0 \sin^2(\pi t / T)$, where the pulse duration is $T = 18\tau \approx 60 fs$ with $\tau$ the laser oscillation period, $a$ is the amplitude of the laser field normalized by $m_e \omega_c / e$ ($\approx 3.2TV / m$). In the simulations, we take the peak amplitude $a_0 = 4.0$, which corresponds to a laser intensity $I_0 = 2.2 \times 10^{19} WI cm^{-2}$. The total size of the simulation box is $75.6\lambda \times 75\lambda$. We put 40 particles per cell and both the longitudinal and transverse spatial revolution is 0.05$\lambda$. The temporal revolution is 0.001$\tau$.

Since the laser pulse normally incidents into an overdense plasma and the plasma density gradient is short enough, electrons are mainly accelerated by the laser ponderomotive force. The constant part of the ponderomotive force introduces a deformation on the target surface and the oscillation part of the ponderomotive force drives the electrons just like a longitudinal electric field and accelerate them into the target.

Figures 2(a)-2(c) show the spatial distributions of the hot electrons with energies larger than 1.533MeV ($\gamma > 3$) in the cone target case at time $60\tau$ (a), $70\tau$ (b), and $80\tau$ (c). The corresponding results for the plane solid target are given in Figs 2(d)-2(f). To examine the effect of electron focusing, we have counted numbers, the average radius, and emitting angles of the hot electrons at different time.

In Table 1. $N_e$ is the number of the hot electrons satisfying $x > 50\lambda$, $\gamma > 3$ at $t = 70\tau$ and $x > 60\lambda$, $\gamma > 3$ at $t = 80\tau$, respectively; The radius $r$ is defined as $r = |y - 750| / 20$ with the laser axis along $y = 750$; the emitting angle is $\theta = \tan^{-1}(P_y / P_x)$. If we assume the system satisfies axis symmetry, we can get the ratio of the line density of the two cases:
Figure 2. (Color online) Spatial distribution of hot electrons. The rectangular region labeled by the red dashed line in (c) corresponds to Fig. 3(d).

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\frac{\rho_{\text{cone}}}{\rho_{\text{flat}}} = \frac{N_{\text{cone}}}{N_{\text{flat}}} \left(\frac{<r>_{\text{cone}}}{<r>_{\text{flat}}}\right)^2 \approx \begin{cases} 5.9 & (t = 70\tau) \\ 2.3 & (t = 80\tau) \end{cases}.
\]

This means the cone target focuses the electrons and the hot electron density increases, although the cone target has lost some hot electrons \(N_{e,\text{cone}} < N_{e,\text{flat}}\). The focusing effect becomes weaker when the hot electrons go forward. This is because some of the hot electrons have been reflected back at the tip of the solid cone as shown later. One notes that the average emitting angle for the cone case is larger than the flat case. The reason is that the momenta along the y direction \(P_y\) for some hot electrons increase while they are focused to the axis of the cone. For both the cone and flat target cases, electrons have scattered once they are ejected into the target center. However, when counting the hot electrons in the center region of the target \(x > 60\lambda, 32.5\lambda < y < 42.5\lambda\), one finds \(N_{\text{cone}} / N_{\text{flat}} = 2552 / 1992 = 1.3\). This means the hot electrons are focused into the target center by the cone target. It is the two-dimensional case, in the three-dimension case this ratio will be 1.69.

### Table 1. Focusing efficiency of cone target vs flat target

| T  | Ne  | <r>  | <θ>  |
|----|-----|------|------|
| 70\tau | cone 6275  | 2.54\lambda | 23.66° |
|     | flat 11378 | 8.32\lambda | 14.19° |
| 80\tau | cone 3596  | 4.08\lambda | 17.23° |
|     | flat 7960  | 9.14\lambda | 12.84° |

In the simulation, we also find: by introducing the cone target, the temperature of the middle energy electrons has been increased and the hot energy tail has been reduced. More hot electrons are in the middle energy region in the cone target case. This is quite beneficial to the inertial confined fusion scheme since too high energetic electrons can preheat the target center and make the ignition defeated.

To see how the hot electrons are focused with the solid cone target, we show the quasistatic field structure at \(t = 80\tau\) in Fig. 3. There are very strong electrostatic fields in the vacuum space between the surfaces of the inner and outer cones. These fields result from the charge separation after the laser radiates the front surface of the inner cone. Electrons accelerated at the beginning of the laser
interactions leave the inner cone and go forward to build the electrostatic fields. Later these fields will confine the succeeding hot electrons and confine them within the inner cone. Besides the electrostatic fields, the quasistatic magnetic fields can also help the focusing process. This kind of confining process is similar with the hollow cone conditions used to focus both the laser pulse and electrons in the experiments by Kodama et al. [7,8]. At the joint region between the inner and outer cone, the quasi-static magnetic fields are in opposite directions. Some electrons located at the edge of the inner cone have been reflected back and transport along the wall of the outer cone as plotted in Fig. 3(d). Most of the inner hot electrons transport forward into the target directly. As a whole, the hot electrons distributed in a mushroom-like structure as shown in Fig. 2(c). In the flat target case, the confinement only takes place at the side walls of the target, and no electron focusing effects. To efficiently focus the hot electrons, the joint region of the inner and outer cone should be designed properly to reduce the reflected electrons.

![Figure 3](image_url)

**Figure 3.** (Color online) Distributions of quasi-static electric fields $E_y$ (a), $E_x$ (b), and magnetic field $B_z$ (c); Frame (d) plots the electron distribution in the space located in the rectangular region marked in Fig. 2(c), where the arrows represent the electron momentum vectors and the corresponding energy of the electrons is larger than 1.533MeV.

3. CONCLUSIONS
By use of 2D PIC simulations we have found that a solid cone target can focus hot electrons. Because of the focusing effects, both the density and temperature of the hot electrons are higher in the cone target case than in the flat target case. The vacuum gap between the inner and outer cone enables to build up huge electrostatic fields there at the beginning, which confine the succeeding hot electrons into the inner cone. Our results may be useful for future target designs either for the purpose of fast ignition experiments or the micro-focusing of relativistic electrons for other applications such as ultrafast radiography and injection of electrons into laser plasma accelerators.

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