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To cite this article: Hong-bo Cai et al 2010 J. Phys.: Conf. Ser. 244 022030

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Collimation of relativistic laser-generated high energy electron beams via double cone target in fast ignition scheme

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\textbf{Abstract.} The success of fast ignitor scheme will ultimately relies on the efficient generation and propagation of enormous number of high-energy charged particles. Particle-in-cell simulations aimed at improving the coupling efficiency of input laser energy deposited to a compressed core by using a double cone are described. Quasistatic magnetic fields generated at the vacuum layer inside the double cones are found to play an important role in confining the high energy electrons. The double cones result in the confinement and focusing of about 15\% of the input energy for deposition in the compressed core.

1. Introduction
In the Fast Ignitor [1], a relativistic electron beam is considered to be the most suitable source for igniting a hot spot much smaller than the dense compressed DT core. In order to improve the efficiency of the coupling and transport of the energy into dense plasma, cone targets\textsuperscript{2,3} have been used in the fast ignition scheme. The merits of cone targets have been shown both in experiments [2] and simulations [4,5].

However, it is found that electrons accelerated by the laser field can escape freely from cone sides to the surrounding coronal plasma, resulting in the decrease of the energy flux through the cone tip. Nakamura et al.[4] have shown that the double cone confines the electrons for hundreds of femtoseconds with an immobile ion background. In their simulations the electrons are blocked by the sheath electric field inside the vacuum gap. However, the plasma expansion could be very significant. Over several hundreds of femtoseconds the sheath electric field inside the gap could be reduced to a very low level. Therefore, important questions arising are: 1) whether the double cone is still effective in confining the high energy electrons after one picosecond, and 2)
how much energy can be confined and focused to the compressed core by using the double cone? These are the principal subjects of this Letter.

2. Numerical study of double cone target

Figure 1(a) is a sketch of the geometry of the simulations. The width of our inner cone wing is 5\(\lambda_0\) and the width of the gap is 3\(\lambda_0\). The plasma consists of three species: electrons, protons with \(m_p/m_e = 1836\) outside the cone, and heavy ions (gold ion with an assumed charge state \(Z_i = 40\)) and \(m_i/m_e Z_i = 195.4/40\). The gold cone, whose edge is drawn with the dashed lines, is surrounded by a hydrogen plasma. Both the plasma density of the gold cone and that of the hydrogen plasma are 40\(n_c\). The \(p\)-polarized laser pulse at \(\lambda_0 = 1.06\mu m\) wave length, and \(1.2 \times 10^{19} W/cm^2\) intensity irradiates the target from the left boundary. The intensity profile is Gaussian in the \(y\)-direction with a spot size of 5\(\lambda_0\). The \(T_0\) is the laser period, after which the laser amplitude is kept constant. A typical simulation duration is 450\(T_0\), which corresponds to about 1.5ps for \(\lambda_0 = 1.06\mu m\).

Here, we use a grid size of \(\Delta x = \Delta y = \lambda_0/64\) with 2800\(\times\)2688 grid cells. The time step used is 0.01\(T_0\). Fifty particles are used in one mesh, and the total number of particles is about \(2.55 \times 10^8\). Both the fields and particles boundary conditions are absorbing boundary conditions, either in the \(x\) and \(y\) direction. In order to eliminate the unphysical sheath field at the boundaries, we set cooling buffers in our simulation. Furthermore, in order to reduce the restrictions on the grid size compared with the Debye length, we used a fourth order interpolation scheme to evaluate fields and currents [6].

To determine the plasma expansion inside the gap, we plot the phase space of high \(Z\) ions in the region \(x \in (25, 30)\lambda_0\) at \(t = 500\, fs\). Clearly, after 1ps of interaction the vacuum gap is filled with plasma a density that can be as high as several critical densities. Thus, we may conclude that we can not expect the sheath electric fields to be still effective in confining high energy electrons after \(t > 1\, ps\).

In Figure 2 the energy density distributions of electrons with energy between \(0.5 \leq E[MeV] \leq 2.0\) are plotted. It is clearly seen that the high energy electrons are mainly accelerated at the cone tip and cone side wall. In the single cone case, some of high energy electrons move freely into the surrounding corona plasma and then

![Figure 1](image1.png)

**Figure 1.** (a) Initial density profile of the double cone target. (b) Phase space of high \(Z\) ions in the region \(x \in (25, 30)\lambda_0\) at \(t = 500\, fs\). (c) A slice of the ion density profile at position \(x = 25\lambda_0\) inside the upper gap of the double cone target. (d) Sketch of collection cone (dark) for the double cone target (green).

![Figure 2](image2.png)

**Figure 2.** The natural logarithm of the electron energy density for single cone (a) and double cone (b) at time \(t = 1000\, fs\).
the energy flux decreases through the cone tip. Alternatively, in the double cone case, few electrons can “leak” out into the surrounding corona plasma even after one picosecond.

Figure 3(a) shows that the sheath electric field peaks at time $t = 250\,\text{fs}$, and eventually decreases to very low level after time $t = 600\,\text{fs}$. In comparison, the quasistatic magnetic field still keeps growing after it grows up at time $t = 330\,\text{fs}$. It is important to stress that the gyro-radius of a typical $1\,\text{MeV}$ hot electron is less than $\lambda_0/2$ under the quasistatic magnetic fields which are the order of $100\,\text{MG}$. Therefore, the electrons escaping into the vacuum gap can be effectively reflected back by the magnetic fields.

### 3. Theoretical analysis of the generation of magnetic fields

In order to evaluate the total energy of the recirculating high energy electrons $Q_h$, we employ

$$
\frac{dQ_h}{dt} = G - Q_h \frac{cS}{3V} (1 - \beta) - Q_h \frac{cS_0}{3V},
$$

(1)

where $G$ is the input laser energy, the second term is the energy flux escaping to the side, $\beta$ is the reflectivity of high energy electrons by the electromagnetic fields, $S$ is the side area, $V$ is the total volume of the system, and the third term is the energy flux emitted from the cone tip. Also, $S_0$ is the area of the cone tip. We assume $|dln\beta/dt| \ll \Omega \equiv cS/3V$, then integrate Eq. (1) to obtain:

$$
Q_h = \frac{G}{\Omega[(1 - \beta) + S_0/S]} \{1 - e^{-\Omega\int_0^t (1 - \beta(t))dt + tS_0/S]}\}. \tag{2}
$$

Eq. (2) indicates that the total energy of high energy electrons increases with time. As a numerical example, we evaluate Eq. (2) for the present double cone case. According to Fig. 3(b), the cone tip area $S_0$ is about $10\,\mu\text{m}^2$ and the side area $S$ is about $40\,\mu\text{m}^2$. On the other hand, simulation shows the flux escaping from the side wall is about $1/4$ of the flux escaping from the tip. Those facts indicate that $(1 - \beta) \approx 0.16$. Since $V \simeq 500\,\mu\text{m}^2$, $\Omega \equiv cS/3V = 8 \times 10^{12}\,\text{s}^{-1}$. So that the electron accumulation time, $\tau_a = [\Omega(1 - \beta) + S_0/S]^{-1} \simeq 0.5\,\text{ps}$. Then $Q_h(t)$ of Eq. (2) is plotted in Fig. 4(a). Note that the quasistatic magnetic field $(B_z(t))$ is proportional to $Q_h(t)$.

The escaped high energy electrons are observed at the boundaries. In the single cone target case only $47.6\%$ of the total absorbed laser energy is contained in the forward energy flux by high energy electrons. When using a double cone, this fraction can be as high as $79.4\%$. In fact, a significant amount of high energy electrons escape from the side walls - about $19\%$ percent of the total input laser energy - is saved for the double cone case compared to that in the single cone case.

In Fig. 3(c) we plot the time-integrated electron energy observed at $x = 40\lambda_0$ as a function of $y$-coordinate. To determine the energy flux of electrons injected into the core, we measure the high energy electrons across a series of planes within the cone; see Fig. 1(d). We found about $14.8\%$ of input laser energy can deposit in the core. In Fig. 3(d) the momentum distribution

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig3.png}
\caption{(a) The maximum values of the quasistatic magnetic field (solid line) and the sheath electric field (dashed line) inside the gap. The dash-dotted line is the plot of $Q_h(t)$ in Eq. (2). (b) The time averaged current $j_x$ at time $1500\,\text{fs}$. (c) The transverse distribution of the energy of the escaped electrons from the right boundary. (d) The natural logarithm of the momentum distribution of the collected high energy electrons.}
\end{figure}
of this group of collected electrons with energy larger than 100keV shows that the double cone target works effectively in collimating and focusing high energy electrons.

4. Wider cone tip size and larger pre-plasma inside the cone
In FIREX-I project in Osaka University, the ignition laser pulse is energy of 10kJ and pulse duration of 1ps to 10ps which is avoidably accompanied by a ns ASE-pedestal. The ASE pulse preheats the target and generates a large pre-plasma. For FIREX-I heating laser, hydrodynamic simulations [7] show that under the irradiance of 1ns ASE pulse with intensity \( I = 10^{11} \text{W/cm}^2 \), the pre-plasma has three segments. In the vicinity of solid density, the scale length is \( \lambda_0 \) and the lower end of the density slop terminates at \( 3n_c \). In over-dense region, the scale length is \( 7\lambda_0 \) and the lower end of the density slop terminates at \( 0.3n_c \). While in the underdense region, the scale length is \( 17\lambda_0 \) and the lower end of the density slop terminates at \( 0.88n_c \); see Fig. 4(a). Here, the cone tip size is \( 6\mu m \). The Gaussian laser pulse rises in 1.6ps and its FWHM duration is 2ps. The laser intensity is \( 1.2 \times 10^{19} \text{W/cm}^2 \) and its spot size is \( 10\mu m \) (FWHM). It is found the pre-plasma plays an important role in the generation of high energy electrons. Fig. 4(b) shows the high energy density at time 2ps. one can see that the high energy electron beam is easily deviated with the laser axis, which introduces some uncertainty for FI. In order to avoid this deviation, double cone target is needed. Computations in this last case are currently in progress, and will be the object of a future publication.

5. Conclusion
In summary, we performed 2D3V-PIC simulations to study the merits of double cone in fast ignition. Our simulation results indicate that the energy flux through the cone tip in the double cone is much larger and more tightly focused than that in the single cone. It has been shown that in the single cone case, the high energy electrons, about 30% of the total input laser energy, escape into the surrounding corona plasma from the side walls. In comparison, in the double cone case the high energy electron flux, about 11% percent of the total input laser energy, escapes from the side walls.

This work was supported by MEXT, a Grant-in-Aid for Creative Scientific Research (15GS0214).

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