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Guiding and confining fast electrons by transient electric and magnetic fields with a plasma inverse cone

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The fast electron propagation in an inverse cone target is investigated computationally and experimentally. Two-dimensional particle-in-cell simulation shows that fast electrons with substantial numbers are generated at the outer tip of an inverse cone target irradiated by a short intense laser pulse. These electrons are guided and confined to propagate along the inverse cone wall, forming a large surface current. The propagation induces strong transient electric and magnetic fields which guide and confine the surface electron current. The experiment qualitatively verifies the guiding and confinement of the strong electron current in the wall surface. The large surface current and induced strong fields are of importance for fast ignition related researches. © 2009 American Institute of Physics. [DOI: 10.1063/1.3075928]

Fast electrons with substantial numbers generated in the intense laser interactions1 have many potential applications, such as fast ignition (FI) of inertial confinement fusion.2 In the FI scheme, the fast electrons propagate into a precompressed core plasma and deposit their energy there for rapid heating to trigger a nuclear fusion burn wave.3,4 This scheme relies on the efficient propagation of fast electrons in the high density plasmas. The propagation process involves three dimensional complex relativistic nonlinear interactions of high density plasmas.10 The transition of fast electron transport from one dimension to two dimension relies on the efficient propagation of fast electrons in the high density plasmas.10 The propagation process involves three dimensional complex relativistic nonlinear interactions of high density plasmas.10 The transition of fast electron transport from one dimension to two dimension (i.e., from a line to a surface) may further help understand the transport process and benchmark the numerical codes for scaling energy requirement of future FI laser facilities.13 It is therefore experimentally desired to guide and confine fast electrons to propagate along a surface for detailed numerical modeling. Surface current of fast electrons, in addition, may play an important role in the specific cone-in-shell target designed for FI.3 Sentoku et al. showed in a particle-in-cell (PIC) simulation that the fast electrons generated at the inner wall of a cone are guided to propagate along the wall surface toward the cone end,12 which might enhance the heating of the core plasma. This surface current was observed with a planar target in both simulation13 and experiments.14,15 However, with a cone target configuration, the guided electrons propagating along the cone wall surface will mix the electrons generated at the cone end by the laser light, and hence one cannot experimentally quantify the numbers of guided fast electrons by the cone wall. The guided fast electrons will also mix the electrons generated ahead by the laser light with a planar target.

We here report a novel surface current of fast electrons propagating in high density plasmas shaped in an inverse cone. The outer tip of the inverse cone faces the incident laser and the inner tip faces the void beneath it. The intense laser irradiates the outer tip, generating fast electrons. The fast electrons are then guided and confined to propagate along the inverse cone wall to form a surface current by the induced transient electric and magnetic fields associated with the current itself. Once departing from the source at the outer tip, this surface current of fast electrons is “clean,” neither experiencing the interacting laser light nor mixing fast electrons ahead, unlike those in cone or planar targets. This surface current in the inverse cone is therefore useful for two dimensional modeling of the large current fast electron transport in high density plasmas, and may also explicitly give the capability of the guiding of fast electrons by the cone wall in a cone-in-shell target.3

The intense laser pulse is injected from the left axially onto the outer tip of an inverse cone plasma, producing fast electrons with substantial numbers and inducing strong transient electric and magnetic fields associated with the fast electron current, as shown in Figs. 1(a)–1(d). Figures 1(a)–1(d) show the distributions of the electric field $E_z$ and magnetic field $B_z$ in the inverse cone plasma at two different times, as generated by a two dimensional PIC simulation,16 showing the fast electron propagation being accompanied by these fields. Figure 1(e) shows the profiles of $E_z$ and $B_z$ at $x=15$ $\mu$m and $t=29.84\tau$, where $\tau\approx3.5$ fs is the laser period. The $p$-polarized 1.06 $\mu$m laser pulse has a spatial pro-

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The fast electrons propagate along the inverse cone wall, inducing strong electric and magnetic fields. (a)–(d) are the distributions of the electric and magnetic fields \( E_x \) and \( B_z \) sliced at 22.38\( \tau \) and 29.84\( \tau \), respectively. (e) shows the strength profiles of \( E_x \) and \( B_z \) at \( x = 15 \mu m \) at time 29.84\( \tau \). \( E_x \) and \( B_z \) are in units of \( 3 \times 10^{10} \text{ V/cm} \) and \( 10^6 \text{ G} \), respectively.

We now experimentally examine the guiding and confinement of the fast electrons with substantial numbers with an Au inverse cone target. The target and experimental setup are shown in Fig. 3(a). The inverse cone target had a 20° full open angle. The outer and inner tip sizes were 100 and 80 \( \mu m \) in diameter, the thicknesses of the tip and the wall were both 7 \( \mu m \), and the length from the tip to the entrance was 600 \( \mu m \), respectively. The experiment was performed on the Gekko XII PW (GXII PW) laser at the Institute of Laser Engineering, Osaka University. The angular distribution of fast electrons emitted forward was measured with a detector stack placed 30 mm behind the target. The stack consisted of several 12 \( \mu m \) thick Al foils, 110 \( \mu m \) CR39s, a 5 mm plastic plate, and two imaging plates (IPs) (Fuji BAS-2R025) as the electron detector. The IPs were wrapped by the Al foils so as to prevent the optical light striking the IPs. The CR39s and the plastic plate may serve as the energy selector for the fast electrons. Electrons with energy higher than 1.8 MeV were recorded on the second IP. In the experiment campaign, the \( p \)-polarized GXII PW laser (\( \lambda = 1.053 \mu m \), \( \tau = 0.6 \text{ ps} \), \( E = 90 \text{ J} \)) had a large focus size of 70–100 \( \mu m \) [full width at half maximum (FWHM)]. The GXII PW laser was focused on the outer tip of the inverse cone, at 26° to the tip normal, with the most intense laser focal spot arranged to deviate from the outer tip of the inverse cone such that only the periphery of the focused laser spot irradiated one edge of the inverse cone outer tip. The main laser pulse thus directly hit the 12 \( \mu m \) thick Al foil. This laser focus arrangement aimed at avoiding the laser irradiation on the outer wall of the inverse cone to generate fast electrons there, which may mix the electrons originating from the inverse cone outer tip, thus giving an explicit evidence of the guiding and confinement of the fast electrons coming from the inverse cone outer tip by the inverse cone wall, as shown in Figs. 1(a)–1(d).

Figure 2 shows the electron kinetic energy density \( (\gamma - 1)n_e/n_e \) distributions snapped at time 59.67\( \tau \). Where \( \gamma = 1/\sqrt{1-v^2/c^2} \) and \( n_e \) is the electron density. It is seen that the electron kinetic energy flux is along the inverse cone wall, showing surface guiding and confinement of the fast electrons, consistent with the electric and magnetic field contours shown in Figs. 1(a)–1(d).

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nal of the upper circular is weaker and centers around point $A$. Point $A$ is on the inverse cone axis, determined by the target and detector alignment, indicating that the inverse cone target contributes to the electron emission in the upper circular shape. The signal of the lower circular is stronger and peaks around point $a$, and gradually fades out radially. Point $a$ in Fig. 3(a) nearly corresponds to the point $a$ in Fig. 3(b) which is behind the point $N$ that is on the GXII PW laser axis, indicating the lower circular emission is due to the laser direct irradiation on the 12 $\mu$m Al foil. The distance between point $a$ and $A$ is about 14 mm, giving the angle between point $M$ and $N$ in Fig. 3(a) relative to the inverse cone target being 25°, nearly equal to the laser incidence angle 26°, consistent to the target, detector, and laser alignment. The fast electron emission from the inverse cone target has a sharp boundary as shown in Fig. 3(c) below, contrary to the fast electron emission from the Al foil shown as the lower circular in Fig. 3(b) where the electron signal gradually fades out radially. There is also no such sharp boundary in the fast electron emission observed with a flat Au target, indicating that there is a clear difference in the fast electron emission pattern between a flat target and the inverse cone target. With the inverse cone target the fast electron emission is confined within a solid angle determined by the sharp boundary shown in Fig. 3(b).

We obtain the fast electron signal purely from the inverse cone target via subtracting the electron signal from the Al foil. We define that $S_B$ and $S_a$ are the electron signal intensities at point $B$ and $a$, respectively. Points $B$ and $a$ move along the lane $AB$ and lane $ab$ in Fig. 3(b) with $aB$
energetic particle imagerings, detailed modeling of the electron transport in high density plasmas, which is essential for FI. The surface current existing in the inverse cone wall could also give the capability of guiding of fast electrons by the cone wall in a cone-in-shell target. Guiding and confining fast electrons with a plasma inverse cone might have several important applications in high energy density physics. One example is to generate collimated or even focused energetic ions, which are emitted from the inner tip into the hollow inverse cone. The inverse cone target is a combination of a foil target and a hollow cylinder target. The collimation of energetic ions with a plasma inverse cone is similar to that with a plasma hollow cylinder, but with a simpler configuration.

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