Generation and optimization of electron currents along the walls of a conical target for fast ignition

S. Micheau[1], A. Debayle[2], E. d'Humières[3], J.J. Honrubia[2], B. Qiao[1],

M. Zepf[1], M. Borghesi[1], and M. Geissler[1]

[1]*Department of Physics and Astronomy, Queen's University Belfast, Belfast BT7 1NN, United Kingdom*

[2] *ETSI Aeronáuticos, Universidad Politécnica de Madrid, Plaza Cardenal Cisneros 3, 28040-Madrid, Spain*

[3] *Université Bordeaux I-CNRS-CEA, Centre Lasers Intenses et Applications, 33405 Talence, France*

Abstract - We present PIC simulations of the laser-cone interaction for the purpose of the HiPER project. The divergence of the fast electron beam emitted at the tip of the cone is a major limitation to the coupling efficiency between the high-energy electrons and the dense core. Here, we show that when the laser spot size is larger than the cone tip, Brunel absorption on the cone walls generates electron currents flowing along the wall surfaces. This produces a convergent electron beam towards the cone axis, thus lowering the fast electrons dispersion. The electron energy distribution obeys a power law completed by a high-energy Maxwelllian tail. We also discuss the influence of various interaction parameters over the formation of these surface currents.

Fast Ignition is an alternate scheme for inertial confinement fusion in which the compression and heating phases of the target are separated in two successive steps. Seminal experiments [1] have recently demonstrated that inserting a hollow cone in the spherical shell results in a significant enhancement of fusion events in the imploded target. The interaction of an intense laser pulse with a conical target has thus been extensively studied, and noticeable differences with respect to the planar geometry have been demonstrated [2, 3]. An important specificity of the laser-cone interaction is the potential formation of electron currents along the cone walls due to self-generated electromagnetic fields [4]. In this paper, we investigate the characteristics of the electron beam emitted at the tip of a conical target irradiated by an ultraintense laser pulse. We present two-dimensional (2D) particle-in-cell (PIC) simulations dedicated to the generation and optimization of surface currents along the sidewalls of the cone, hence producing a convergent fast electron beam towards the cone axis.

The simulations are performed with the fully relativistic PIC codes ILLUMINATION [5] and PICLS [6]. The simulation box is made of 2550×2048 cells with a mesh size of 16*16 nm^2. The laser pulse is p-polarized, with a wavelength of 1 μm, and a duration of 100 fs. The temporal and spatial profiles are both gaussian. The target geometry consists of a 30° full-angle hollow cone, with 2.5 μm thick walls. The cone tip inner size is d=10 μm and its thickness is 2.5 μm. The target is made of a collisionless plasma with immobile ions, and its density is 10n_c (n_c is the critical density). We checked that using mobile Au$^+$ ions do not lead to any differences in the results obtained due to the short pulse duration employed in our simulations. The cone is filled with an exponentially decreasing preplasma, whose scale length is 1 μm and 0.25 μm in front of the cone tip and the walls, respectively, to ensure the density continuity. The electron population is simulated by 64 particles per cell. A dense plasma slab of 4.5 μm thick is placed behind the cone tip which mimics the coronal plasma and limits the refluxing of electrons towards the inner part of the cone. To characterize the fast electron beam emitted at the cone tip, we follow the trajectories of about 8 millions of quasiparticles. At each timestep, we extract the particles crossing the cone tip with an energy threshold of 500 keV. Due to the electromagnetic fields building up at the cone tip (enhanced by the immobile ions) and the limited size of the coronal plasma, some particles are bounced back and forth across the cone tip. These particles crossing the surface several times are thus not considered. We checked that a larger coronal plasma (14.5 μm thick) gives similar results to the ones presented here, the differences arising only in the power law factor or the temperature of the electron energy spectra. We performed two sets of simulations. In the first case, the laser spot size is $w_{1/e}$=3 μm, and is thus smaller than the cone tip inner size. In the second case, the spot size is 12 μm in order to investigate the contribution of the walls to the fast electron beam. The laser peak intensity is kept identical in both cases at I_0=5.5×10^{20} W/cm^2 (a_0=20). Fig. 1(a) displays the time-integrated electron energy flux crossing the cone tip
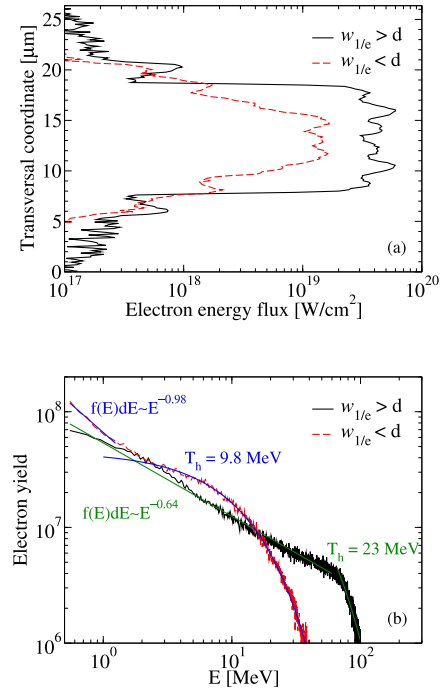

Figure 1: Time-integrated transversal distribution of the hot electron energy flux crossing the cone tip (a) and time-integrated electron energy spectra (b) when the laser spot size is larger than the cone tip size (solid line), and when the laser spot size is smaller than the cone tip size (dashed line).

as a function of the transversal coordinate. When $w_{1/e} < d$, the spatial distribution resembles the gaussian profile of the laser pulse. When the laser pulse interacts with the cone walls, the spatial profile is mostly flat, and its dimension matches the inner cone tip size. This supports previous findings suggesting that the fast electron beam extension is controlled by the cone tip size [7]. The two peaks seen at 10.6 μm and 15.6 μm in the spatial energy flux distribution when $w_{1/e} > d$ are due to electrons flowing along the inner surfaces of the cone walls. This can be seen in Fig. 2(a) where the instantaneous longitudinal component of the current is shown, and in Fig. 2(b) which exhibits typical trajectories of electrons that are initally sampled 2 μm around the inner walls surfaces. The laser pulse interacting obliquely with the cone sides generates electron currents along the walls, thus producing convergent electron flows towards the cone axis. The electron bunches are distributed regularly with $\lambda / \sin \theta$ intervals, where θ is the incident angle on the walls. This is the signature of Brunel-type absorption mechanism [8]. The time-integrated energy spectra for the two laser spot sizes are shown in Fig. 1(b). Both spectra are fitted by a power law followed by a high-energy Maxwellian tail. The higher temperature and the wider range of energies fitted by a power law in the case of the larger spot size are the results of the Brunel absorption and the subsequent surface acceleration on the sidewalls of the cone. A similar enhancement in the temperature has also been observed experimentally when the laser pulse was focused on the cone walls rather than on the cone tip [3]. To demonstrate the focusing effect of the cone, we present in Fig. 2(c) the map of the electron energy flux crossing the cone tip surface as a function of the transversal coordinate and the direction of emission of the electrons (with respect to the laser propagation direction). A pattern is clearly observed, showing that electrons from the upper part of the cone ($x > 13.3$ μm) are mainly going downwards, whereas electrons generated in the lower part ($x < 13.3$ μm) are mainly going upwards. The guiding of electrons along the walls thus generates a convergent fast electron beam towards the cone axis. In addition, we also performed simulations to investigate the influence of the interaction parameters over the generation of electron flows along the cone walls. The strength of the surface currents is enhanced when the normalized laser intensity increases with respect to the density normalized to the critical density. Using a shorter wavelength for the ignition beam could be considered, as it lowers the electron average energy without lowering the currents strength. In any case, the laser contrast has to be maximised to limit the preplasma filling the cone.

In conclusion, the interaction of the laser pulse with the cone walls is highly beneficial as the formation of electron currents guided along the wall surfaces results in a focused fast electron beam, which can remain collimated by self-generated magnetic fields [10]. In all our simula-
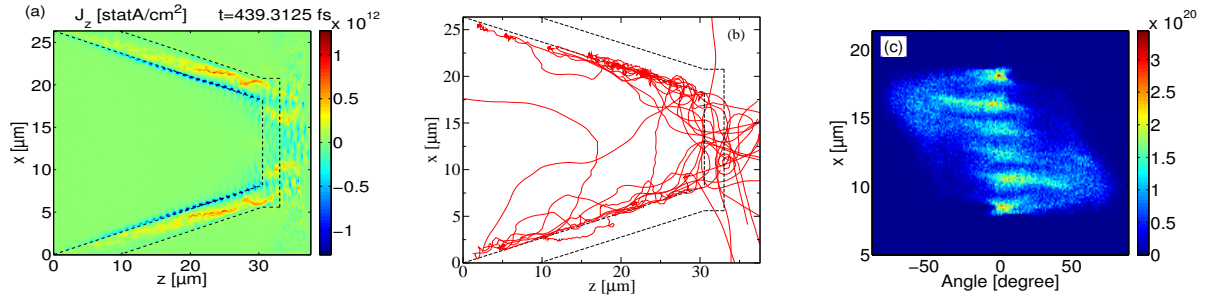
Figure 2: Instantaneous longitudinal component of the electron current (a) and typical electron trajectories (b) obtained when $w_{1/e} > d$. The dashed lines indicate the initial position of the cone. (c) Distribution of the hot electron energy flux crossing the cone tip as a function of the transversal coordinate and the direction of emission when $w_{1/e} > d$.

tions, we find that the energy distribution function obeys a power law completed by a high-energy Maxwellian tail. Since hybrid simulations have shown that ignition is sensitive to the electron energy spectrum, a more accurate consideration of the energy distribution in the fast electron transport codes is thus desirable for fast ignition. Finally, the results presented here are limited to short pulse durations. Longer pulse simulations have thus to be performed to investigate the influence of the processes appearing over longer timescales.

References

[1] R. Kodama et al., Nature (London) **412**, 798 (2001).

[2] Z. L. Chen et al., Phys. Rev. E **71**, 036403 (2005); M. Nakatsutsumi et al., Phys. Plasmas **14**, 050701 (2007); J. A. King et al., Phys. Plasmas **16**, 020701 (2009).

[3] H. Nakamura et al., Phys. Rev. Lett. **102**, 045009 (2009).

[4] Y. Sentoku et al., Phys. Plasmas **11**, 3083 (2004).

[5] M. Geissler et al., New J. Phys. 8, 186 (2006); M. Geissler et al., ibid **9**, 218 (2006).

[6] Y. Sentoku and A. Kemp, J. Comput. Phys. 227, 6846 (2008).

[7] T. Nakamura et al., Phys. Plasmas **14**, 103105 (2007).

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

[9] H. Cai et al., Phys. Plasmas **17**, 023106 (2010).

[10] J. J. Honrubia and J. Meyer-ter-Vehn, Plasma Phys. Controlled Fusion 51, 014008 (2009).