Simulations of electron-beam transport in solid-density targets and the role of magnetic collimation

A. A. Solodov, M. Storm, J. F. Myatt, R. Betti, D. D. Meyerhofer, P. M. Nilson, W. Theobald, and C. Stoeckl

Fusion Science Center and Laboratory for Laser Energetics, University of Rochester, Rochester, NY 14618

E-mail: asol@lle.rochester.edu

Abstract. Three-dimensional simulations of solid-target electron-transport experiments have been performed, using the hybrid-PIC code LSP. The experimentally observed fast-electron divergence half-angle of 16° in the target was reproduced assuming an initial divergence half-angle of ~56°, close to the value expected from the simple ponderomotive acceleration formula: \[ \theta_{1/2} = \tan^{-1}\left(\frac{1}{\gamma}\right) \], where \( \gamma \) is the electron relativistic factor. The simulations accurately reproduce the details of the electron transport observed in the experiment. The electron beam propagates as an expanding annulus that breaks into filaments due to the resistive filamentation instability. The electron-beam partial collimation and annular propagation is due to the resistive azimuthal magnetic field generated at the outer edge of the electron beam.

1. Introduction

Powerful lasers focused onto the surface of a solid, produce large numbers of energetic electrons. Such energetic electrons can be used in the fast ignition approach to inertial confinement fusion (ICF). In fast ignition ICF [1] a laser generated beam of energetic electrons deposits its energy inside a precompressed deuterium-tritium fuel pellet, heating a small hot spot fast enough before the fuel expands hydrodynamically. Fast ignition requires that the energetic electrons remain collimated as they propagate through the target. Early experiments using multiterawatt laser systems observed a collimated fast electron flow in low \( Z \) targets [2]. Later experiments using imaging of \( K_{\alpha} \) emission from high \( Z \) buried layer targets (see Ref. [3] and references therein) measured a divergent electron flow with half-angle divergence increasing with the laser intensity: from \( \theta_{1/2} = 12^\circ \) at \( \mathcal{I} = 3 \times 10^{18} \) W/cm\(^2\) to \( \theta_{1/2} = 27^\circ \) at \( \mathcal{I} = 5 \times 10^{20} \) W/cm\(^2\) according to Fig. 2 of Ref. [3]. Hot-electron collimation in the experiments of Ref. [2] was explained by the presence of self-generated resistive magnetic fields [4]. Recent two-dimensional hybrid-particle-in-cell (PIC) simulations [5] showed that the effectiveness of magnetic collimation decreases with the laser intensity and that the experiments of Ref. [3] can be explained by a partial (not-complete) collimation of hot electrons. It has been, however, noticed [5] that more complete three-dimensional simulations including the details of the resistivities for the target materials are required for a better quantitative agreement of the electron divergence half-angle in the experiments and simulations.
Here we report the results from three-dimensional (3D) hybrid-PIC simulations of the electron-transport experiments recently performed at the Laboratory for Laser Energetics [6]. In this work, the effects of the target resistivity, including different target ionization levels, have been studied in detail. This detailed analysis provides more accurate modeling of resistive magnetic fields and electron transport than in Ref. [6] where electron collimation depended on the degree of target ionization (assumed to be fixed). The simulations confirm that electron transport can be explained by partial collimation of hot electrons by resistive magnetic fields. The initial divergence half-angle of the hot electrons in the target is found to be close to the value predicted by the ponderomotive scaling.

2. Summary of experiments
The experiments were conducted on the Multi-Terawatt (MTW) Laser Facility at the University of Rochester’s Laboratory for Laser Energetics. A laser pulse of wavelength $\lambda_L = 1.053 \, \mu m$, with an energy of $\sim 5 \, J$ and a duration of $\Delta t_L \sim 650 \, fs$, was focused with normal incidence to a 4-$\mu m$-radius spot, producing an intensity of $\sim 10^{19} \, W/cm^2$. The Al, Cu, Sn, and Au foil targets had transverse dimensions of 500 $\mu m$ and thicknesses ranging from 5 to 100 $\mu m$. A coherent transition radiation (CTR) diagnostic was fielded to acquire images of the rear-side optical emission with a spatial resolution of $\sim 1.4 \, \mu m$.

Figure 1 shows three images of the rear-side emission plotted in arbitrary units of intensity. From left to right, the targets are 20-$\mu m$-thick Al, 30-$\mu m$-thick Al, and 50-$\mu m$-thick Cu. The emission contains small-scale structures, with a mean diameter of $\sim 4.0 \, \mu m$, superimposed on a larger annular feature whose diameter increases with target thickness.

Figure 2 shows how the size of the rear-surface emission region grows with target thickness. No dependence on the target material was observed. The half-angle electron-beam divergence was inferred to be $\theta_{1/2} = 16^{\circ}$ using a least-squares linear fit.

3. The simulation model and parameters
The three-dimensional hybrid-PIC code LSP [7] has been used to model the transport of hot electrons in solid targets. The collisional model in LSP has been recently modified to include relativistic effects for hot electrons [5]. Separate species for hot electrons in different energy ranges are used to insure the correct scattering and slowing-down rates for electrons at different energy levels. The collisional model was tested to reproduce the correct ranges, blooming, and straggling of hot electrons, the correct scattering and slowing-down rates for electrons at different energy levels. The collisional model in LSP has been recently modified to include relativistic effects for hot electrons [5]. Separate species for hot electrons in different energy ranges are used to insure the correct resistive electric and magnetic fields, and to conserve energy. The simulations shown in this paper use the Thomas-Fermi ionization model [8] and equation of state [9] to calculate changes in the ionization state and specific heat capacity of the background electrons with the target temperature. The simulations also use the Lee and More resistivity model [10].

Hot electrons are promoted from the background of plasma electrons at the left-hand-side target boundary, having an exponential energy distribution, $\sim \exp(-E/\langle E_i \rangle)$. The mean energy is given by the maximum of the ponderomotive [11] and Beg [12] scalings:

$$\langle E_i \rangle [MeV] = \max \left\{ 0.51 I \left[ 1 + I \frac{\lambda_0^2}{2.8 \times 10^{18}} \right]^{1/2} - 1 \right\}^{1/3} \left[ 0.1 \left( \frac{\lambda_0^2}{10^{17}} \right) \right]^{1/3}.$$
Gaussian in space and time laser pulse having the maximum intensity of $1.44 \times 10^{19} \text{ W/cm}^2$, full width at half-maximum (FWHM) of 5.54 $\mu\text{m}$, and duration $\tau=650$ fs. The energy conversion efficiency to hot electrons is 20%, in agreement with LSP simulations of the experiments on MTW [13]. Similar conversion efficiencies for the present intensities were reported by others [14]. Electrons with energy $E_{e}=\gamma mc^{2}$ are randomly injected in a cone with a half-angle $\theta_{1/2}=\alpha \tan^{-1}\left[\sqrt{2/(\gamma-1)}\right]$ which for $\alpha=1$ describes the angle at which electrons are ejected from a focused laser beam by the ponderomotive force [15]. Simulations have been performed for different parameters $\alpha$ and Al targets with thicknesses 20-100 $\mu\text{m}$ and transversal dimensions of 120 $\mu\text{m}$.

4. Simulation results

Figure 3 (a) shows cross sections through the azimuthal magnetic field 350 fs after the peak of the laser pulse in the simulation for $\alpha=1$ and 60-$\mu\text{m}$ thick target. Figure 3 (b) shows the location of the hot-electron-density isosurface (red-solid) at 50% of the peak density in each transverse plane at the same moment of time; the blue semi-transparent surface corresponds to the case with the magnetic field artificially suppressed. The hot-electron beam is partially collimated by the resistive magnetic field generated at the outer edge of the electron beam. This field is most intense in the first 20 $\mu\text{m}$ in the target. The magnetic field reduces the initial beam divergence half-angle of $\theta_{1/2} \approx 56^\circ$ (averaged within the FWHM of the beam spatial and temporal distribution) to $\theta_{1/2} \approx 16^\circ$, close to the beam divergence half-angle in the experiment. The variation of the beam density distribution with the propagation distance resembles an expanding annulus which breaks into filaments due to the resistive filamentation instability. Electron beam develops an annular shape because electrons propagating at larger angles to the axis are deflected by the edge magnetic field more than electrons propagating at smaller angles. The electron angular distribution peaks at about 16$^\circ$ to the axis and the density distribution develops a peak at the beam edge. The annular beam distribution is reinforced by magnetic fields generated at the inner and outer sides of the annulus, having opposite signs and collimating electrons into the annular region.

The collimating effect of magnetic field is significant, as it is seen from comparison of the beam density isosurfaces with and without magnetic field in Fig. 3 (b). The magnetic field, however, is not sufficient to completely collimate the beam because of its high initial divergence. Figures 4 and 5 compare the results of simulations for different $\alpha$. The divergence half-angle increases (Fig. 4) from 0$^\circ$ (complete collimation) for $\alpha \leq 0.7$ to more than 16$^\circ$ for $\alpha > 1$. Figure 5 shows the hot-electron-density distributions (for electrons with $E=0.25 \text{ MeV}$) on the back of a 50-$\mu\text{m}$ thick target, averaged in time using $\int n(r,t)dt/1.065\tau$, for three values of $\alpha$: $\alpha=0.7$, 1, and 1.2. The annular density distribution in Fig. 5 (b) for $\alpha=1$ is similar to the CTR distributions in Fig. 1. Notice that CTR is thought to be produced by the high-energy part of the hot-electron distribution. We studied the spatial distributions of electrons with energies between 1.5 MeV and 2 MeV and above 2 MeV (representing a relatively small fraction of electrons) and found similar annular distributions as for the bulk of hot electrons in Fig. 5 (b).
5. Summary

3D hybrid-PIC LSP simulations are shown to reproduce the details of electron transport in the experiments on MTW. The hot electrons are partially collimated by the self-generated resistive magnetic field. The electron beam propagates as an expanding annulus that breaks into filaments due to the resistive filamentation instability. The experimentally observed fast-electron divergence half-angle of 16° has been reproduced for Al targets assuming an initial divergence half-angle in the target of ~56°, close to the value expected from the simple ponderomotive acceleration formula. Similar results were obtained in the simulations using approximate models for the plasma resistivity and specific heat capacity, when a constant degree of ionization of 8 for Al plasma was used [6]. Simulations for higher-Z targets are in progress. Preliminary results show more-diffused (less-spiky) electron-beam density distributions due to enhanced electron scattering in the target. The overall divergence of hot electrons, however, is not increased for sufficiently thin targets for which the CTR signal in the experiment was distinguishable [6], generally thinner than the hot-electron mean-free pass. These simulations will be reported elsewhere.

6. Acknowledgments

This work was supported by the U.S. Department of Energy under Cooperative Agreement DE-FC02-04ER54789 (Fusion Science Center, Office of Fusion Energy Science) and DE-FC52-08NA28302 (Office of Inertial Confinement Fusion), the University of Rochester, and the New York State Energy Research and Development Authority. The support of DOE does not constitute an endorsement by DOE of the views expressed in this article.

References

[1] M. Tabak et al., Phys. Plasmas 1, 1626 (1994).
[2] M. Tatarakis et al., Phys. Rev. Lett. 81, 999 (1998); M. Borghesi et al., Phys. Rev. Lett. 83, 4309 (1999); L. Gremillet et al., Phys. Rev. Lett. 83, 5015 (1999).
[3] J. S. Green et al., Phys. Rev. Lett. 100, 015003 (2008).
[4] A. R. Bell and R. J. Kingham, Phys. Rev. Lett. 91, 035003 (2003).
[5] A. A. Solodov, K. S. Anderson, R. Betti, et al., Phys. Plasmas 16, 056309 (2009).
[6] M. Storm, A. A. Solodov, J. F. Myatt, et al., Phys. Rev. Lett. 102, 235004 (2009).
[7] D. R. Welch et al., Phys. Plasmas 13, 063105 (2006).
[8] R. M. More, Adv. At. Mol. Phys. 21, 305 (1985).
[9] A. R. Bell, Rutherford Appleton Laboratory Report RL-80-091, 1980 (unpublished).
[10] Y. T. Lee and R. M. More, Phys. Fluids 27, 1273 (1984).
[11] S. C. Wilks and W. L. Krueer, IEEE J. Quantum Electron. 33, 1954 (1997).
[12] F. N. Beg et al., Phys. Plasmas 4, 447 (1997).
[13] P. M. Nilson, W. Theobald, J. F. Myatt, et al., Phys. Rev. E 79, 016406 (2009).
[14] K. Yasuike et al., Rev. Sci. Instrum. 72, 1236 (2001).
[15] C. I. Moore, J. P. Knauer, and D. D. Meyerhofer, Phys. Rev. Lett. 74, 2439 (1995). 

FIG. 4 Divergence half-angle versus $\alpha$.

FIG. 5 Rear-surface transverse-density distributions of hot electrons for the 50-µm thick target.