The Role of Self-Generated Magnetic Fields and Resistive Filamentation in Hot-Electron-Beam Transport Through Solid Targets


Fusion Science Center and Laboratory for Laser Energetics
University of Rochester
Three-dimensional simulations of solid-target electron-transport experiments at the Laboratory for Laser Energetics 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 $\theta_{1/2} = \tan^{-1}\left[\sqrt{2/(\gamma - 1)}\right]$, 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. Our simulations also explain the observed annular-shape electron-beam structure in experiments performed by other groups.
Electron-transport measurements are successfully modeled with $LSP^1$.

- Characteristics of electron transport in high-intensity laser–target interaction have been inferred using Coherent Transition Radiation (CTR).
- Filamentation and divergence of the CTR in solid planar targets with variable thickness was observed.
- Self-generated magnetic fields and resistive filamentation are observed in $LSP$ simulations and explain the experimental observations.
- The hot-electron divergence half-angle of $\sim 16^\circ$ in the target is reproduced in $LSP$ simulations assuming an initial divergence half-angle of $56^\circ$, approximately the ponderomotive angle.
Experiments were conducted on the Multi-Terawatt (MTW) Laser Facility at the Laboratory for Laser Energetics to study electron transport.

- Al, Cu, Sn, and Au foil targets with transverse dimensions of 500 μm and thicknesses ranging from 5 to 100 μm were used.

MTW laser

$E_0 = 5 \text{ J}$

$I_0 = 10^{19} \text{ W/cm}^2$

$T_0 = 650 \text{ fs}$

$r_0 = 5 \text{ μm}$

Divergent hot-electron transport diagnosed with CTR
A Coherent Transition Radiation (CTR) diagnostic was fielded to acquire images of the rear-side optical emission with a spatial resolution of \(~1.4\ \mu m\).

- The CTR images show bright, small-scale structures superimposed on a larger annular structure.
The transverse size of the rear-surface emission grows with the target thickness, indicating a half-angle divergence of $16^\circ$

$$\theta_{1/2} \approx 16^\circ \pm 1^\circ$$

- No dependence on the target material was observed and each experimental point represents the radial size averaged over all materials.
Three-dimensional transport of fast electrons in Al targets have been modeled\(^1\) using the hybrid-PIC code \(LSP\)^2

**Electron-beam parameters:**

- Laser intensity: \(I = I_0 \exp \left[ -\frac{r^2}{r_0^2} \left( t - t_0 \right)^2 / \tau_0^2 \right] \)
- Hot-electron distribution function: \(f(E) \sim \exp \left( -\frac{E}{\langle E_h \rangle} \right)\), where
  \[
  \langle E_h \rangle [\text{Me V}] = \max \left\{ 0.511 \left( 1 + I \lambda_0^2 / 2.8 \times 10^{18} \right)^{1/2} - 1, 0.1 \left( I \lambda_0^2 / 10^{17} \right)^{1/3} \right\}
  \]
  (ponderomotive\(^3\) and Beg’s\(^4\) scalings)
- Energy-conversion efficiency\(^5\) = 20%  
- Initial divergence: electrons with \(E_h = (\gamma - 1) mc^2\) are randomly injected in a cone with half-angle \(\theta_{1/2} = \alpha \tan^{-1}\left[ \sqrt{2/\gamma - 1} \right]; \ \alpha = 1–\text{ponderomotive angle.}\(^6\)

**Two methods for plasmas resistivity:**

1. Spitzer resistivity saturated at low temperature \(\eta = 1 / \sqrt{\eta_{\text{max}}^{-2} + \eta_{\text{Sp}}^{-2}}\), where \(\eta_{\text{max}} = 1.6 \times 10^{-6} \ \Omega m, 6\times, 8\times, \text{and } 10\times \text{ionized Al plasma}\)
2. Lee and More resistivity model\(^7\) + Thomas–Fermi ionization model and equation of state\(^8\)
Hot electrons are partially collimated by a self-generated resistive azimuthal magnetic field in LSP simulations.

Azimuthal magnetic field (MG), $\alpha = 1$, 350 fs after the peak of the pulse.

Hot-electron density isosurface at 50% of the peak density in $(x,y)$ plane with and without magnetic field.

- Electron beam develops annular structure and breaks into filaments due to resistive filamentation instability.
The hot-electron divergence half-angle of $\sim 16^\circ$ is reproduced in LSP simulations, assuming an initial divergence half-angle of $56^\circ$ ($\alpha \approx 1$).

Methods (2) and (1) with $8 \times$ ionized Al plasma

- Method (1), $6 \times$ and $10 \times$ ionized plasma: $\alpha$ should be changed by 7% to 8% to reproduce the divergence half-angle in the experiment.
The size of rear-surface annular electron-beam density distribution increases with the initial divergence of hot electrons.

50-µm-thick Al target

Time–averaged, rear–surface density distributions of electrons with $E > 0.25$ MeV (in units of $10^{20}$ cm$^{-3}$) for different $\alpha$

![Graphs showing density distributions for different $\alpha$ values](image)
LSP simulations for $\alpha = 1$ predict rear-surface, transverse-density distributions of electrons for different thicknesses of Al, which resemble the measured rear-surface CTR distributions.

Time-averaged density of electrons with $E > 0.25$ MeV (in units of $10^{20}$ cm$^{-3}$)
References


