Controlling the Divergence of Laser-Generated Fast Electrons Through Resistivity Gradients in Fast-Ignition Targets

A. A. Solodov
University of Rochester
Laboratory for Laser Energetics

41st Annual Anomalous Absorption Conference
San Diego, CA
19–24 June 2011
Summary

Divergence of high-energy electron beams can be controlled through resistivity mismatch in fast-ignition targets*

- LSP** simulations predict collimation of high-energy electron beams by resistivity gradients
- Four cases have been modeled
  - Cu cone
  - Al cone with Cu insert in the cone tip
  - Al cone with a Cu wire attached to the cone tip – most effective
  - Cu-lined diamond cone

Collimation by resistivity gradients increases the coupling to the core.


University of Rochester
Laboratory for Laser Energetics and Fusion Science Center
Self-generated resistive magnetic fields can control divergence of electron beams in plasmas*

- Electron collimation by B fields generated by resistivity gradients*

\[ j_h = j_h(r) \]

\[ \hat{E} = \eta j_p \approx -\eta j_h \]

\[ \frac{\partial \vec{B}}{\partial t} = -\nabla \times \vec{E} \]

\[ \frac{\partial \vec{B}}{\partial t} = \eta \nabla \times j_h + \nabla \eta \times j_h \]

A thin Cu fiber embedded in Al effectively collimates a highly divergent 15-kJ electron beam in the LSP simulation.

- Simulation for a 7-ps, 2-MeV mean-energy, 67° half-angle electron beam

- Even though $\nabla \eta$ changed direction due to fiber heating, collimation is maintained because $|\eta \nabla \times \vec{j}_h|$ becomes greater than $|\nabla \eta \times \vec{j}_h|$.

Collimated electrons contain 65% of the beam energy.
Electron transport in fast-ignition targets using materials with different resistivities has been modeled with LSP.

- Electron beam: $E_{\text{tot}} = 40 \text{ kJ}$, $\tau = 10 \text{ ps}$, $r_0 = 20 \mu m$, $T_{\text{hot}} = 1.6 \text{ MeV}$, $\theta_{1/2} = 67^\circ$
- Ionization and radiative cooling are modeled
- Energy coupled to the “ignition region” is calculated and compared in the simulations
Electrons are effectively collimated by resistivity gradients in the cone tip and in the wire.
Hot-electron divergence is controlled by a resistive magnetic field

<table>
<thead>
<tr>
<th>Cu cone</th>
<th>Al cone with Cu insert</th>
<th>Al cone with Cu wire</th>
</tr>
</thead>
</table>

**Electron-beam density (cm$^{-3} \times 10^{22}$)**

**Azimuthal magnetic field (MG)**
Resistive collimation significantly improves electron coupling to the core

- Resistive collimation can be especially useful for targets with thick cone tips

<table>
<thead>
<tr>
<th>Cu cone</th>
<th>Al cone with Cu insert</th>
<th>Al cone with Cu wire</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Cu cone diagram" /></td>
<td><img src="image2" alt="Al cone with Cu insert diagram" /></td>
<td><img src="image3" alt="Al cone with Cu wire diagram" /></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Energy coupled to the “ignition region”</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.7 kJ (7%)</td>
</tr>
</tbody>
</table>

TC9079a
Hydrodynamic simulations are required to determine survivability of the wire during the implosion.

- The wire is compressed radially and longitudinally during the implosion.
- Asymmetric implosions may be advantageous:
  - to protect the wire and the cone from the pressure build-up in the central hot spot
  - to facilitate ignition because of a larger fuel density and larger $\rho R$ in front of the wire.
1-D *LILAC* simulations of capsule implosion on a copper sphere and a copper cylinder predict the compressed copper properties.

**Simulations use a 200-kJ DT target design for direct-drive fast ignition**

- Increased stopping power in a compressed copper may require using higher-energy electrons for ignition (2 to 5 MeV)

<table>
<thead>
<tr>
<th></th>
<th>Diameter (μm)</th>
<th>Density (g/cm³)</th>
<th>Temperature (eV)</th>
<th>Cu resistivity (Ω × m)</th>
<th>DT resistivity (Ω × m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu sphere</td>
<td>26</td>
<td>500</td>
<td>600</td>
<td>7 × 10⁻⁸</td>
<td>10⁻⁹</td>
</tr>
<tr>
<td>Cu cylinder</td>
<td>26</td>
<td>150</td>
<td>275</td>
<td>2 × 10⁻⁷</td>
<td>10⁻⁸</td>
</tr>
</tbody>
</table>


**R. Betti and C. Zhou, Phys. Plasmas 12, 110702 (2005).*
Electron collimation by a high-resistivity material at the inner-cone surface has been modeled

- Diamond cone with Cu tip and Cu inner layer
- Cu pre-plasma: $\rho = 0.02 \rho_{\text{solid}}$ with 1.5-$\mu$m exponential gradient length at the cone surface
- Electron beam: $E_{\text{tot}} = 300$ J, $\tau = 10$ ps, $r_0 = 14$ $\mu$m, $T_{\text{hot}} = 1$ MeV, $\theta_{1/2} = 67^\circ$
Hot-electron collimation in a Cu-lined cone is not as effective as in the wire.

- Simulation results at $t = 5$ ps

Electrons collimated to the cone tip contain 17% of the beam energy.
Divergence of high-energy electron beams can be controlled through resistivity mismatch in fast-ignition targets

- *LSP** simulations predict collimation of high-energy electron beams by resistivity gradients

- Four cases have been modeled
  - Cu cone
  - Al cone with Cu insert in the cone tip
  - Al cone with a Cu wire attached to the cone tip – most effective
  - Cu-lined diamond cone

Collimation by resistivity gradients increases the coupling to the core.


**D. R. Welch et al., Phys. Plasmas 13, 063105 (2006).*