Integrated Simulations of Hot-Electron Transport and Ignition for Direct-Drive, Fast-Ignition Targets

300-kJ fuel assembly
e-beam: Maxwellian, $\langle E \rangle = 2$ MeV
$r_{\text{FWHM}} = 30 \, \mu m$
opening half angle = 20°
$E_{\text{total}} = 43 \, kJ$

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Electron-beam collimation by a self-generated resistive magnetic field increases the coupling efficiency of hot electrons with the target and reduces the energy required for ignition.

- The hybrid-PIC code $LSP^1$ and the fluid code $DRACO^2$ have been integrated for simulations of hot-electron transport and ignition for direct-drive, fast-ignition fusion targets.
- Integrated simulations show ignition of optimized spherically symmetric targets$^3$ by a 43-kJ, 2-MeV Maxwellian electron beam.
- Simulations of plastic cone-in-shell targets designed for OMEGA-integrated experiments show heating by up to 1 keV and a neutron yield of $1.6 \times 10^{10}$.

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References:

Collaborators

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Modeling the entire fast-ignition experiment requires resolving very different spatial and temporal scales and using different types of codes.

- A target implosion is simulated using hydrocodes.
- Generation of hot electrons by a petawatt laser pulse interacting with a solid target or coronal plasma is simulated using particle-in-cell (PIC) codes.
- Hot-electron transport to the target core is simulated using hybrid-PIC or Monte Carlo codes.

We have integrated the hydrocode DRACO and hybrid-PIC code LSP to model the fast-ignition experiment.
LSP simulates the hot-electron transport and energy deposition, and DRACO is used to simulate the target hydrodynamics and burn

- **DRACO**
  - 2-D cylindrically symmetric hydrodynamic code
  - includes all the necessary physics required to simulate ignition and burn of the imploded capsules

- **LSP**
  - 2-D/3-D implicit-hybrid PIC code
  - implicit solution for the electromagnetic fields and implicit particle push
  - hybrid fluid-kinetic description for plasma electrons with dynamic reallocation
  - intra- and interspecies collisions based on Spitzer rates (have been corrected to include relativistic effects)
  - uses ideal gas equation of state
**LSP** generates a hot-electron source term in the temperature equation solved by **DRACO**

- **LSP** generates the time history of hot-electron-energy deposition in plasma for **DRACO**.

- Hydrodynamic profiles in **LSP**: electron and ion temperatures, densities, and velocities are periodically updated according to **DRACO** results (fluid species). Electromagnetic fields and hot-electron distributions (kinetic species) are not changed.

- In **LSP**, hot electrons are promoted from background electrons with a mean energy predicted by PIC simulations*.

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In the integrated simulation, an imploded optimized fast-ignition target* is heated by a 2-MeV, FWHM = 30-μm electron beam.

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Integrated simulation shows electron beam collimation by the self-generated resistive magnetic field and resistive filamentation$^{1,2}$

Snapshots at $t = 8$ ps after the beginning of the e-beam

Plasma density ($\times 10^{26} \text{ cm}^{-3}$)

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

Plasma electron temperature (keV)

Azimuthal magnetic field (MG)

Total e-beam energy = 43 kJ, angular divergence = 20°

Beam collimation and resistive filamentation in LSP simulations are in agreement with theoretical predictions\textsuperscript{1,2,3}

- LSP reproduces correctly the analytic magnetic field for a rigid Gaussian electron beam\textsuperscript{3}
- The resistive filamentation instability growth rate in the simulations is in agreement with Ref. 1

Electron-beam density ($\times10^{22}$ cm\textsuperscript{-3})

$$\Gamma^\text{theory} = \frac{2}{\tau_d \gamma_b} \left( \frac{\beta_b}{\beta_b^{\text{th}}} \right)^2$$, where $\tau_d = \mu_0 c^2 / (\eta \omega_b^2)$; $\Gamma^\text{theory} \approx 1.7 \times 10^{12}$ s\textsuperscript{-1} at $t = 1.5$ ps

Ignition is triggered by a 43-kJ e-beam in the integrated simulation.
Simulation with the magnetic field artificially suppressed predicts a minimum energy for ignition of 96 kJ for the same e-beam properties.

Beam collimation by the resistive magnetic field reduces the energy required for ignition.
Integrated OMEGA experiments using low-adiabat implosions of plastic cone-in-shell targets* and PW heating pulses from OMEGA EP will be performed soon.

We have performed simulations of target heating for integrated OMEGA experiments

- Hydrodynamic simulations of cone-in-shell target implosions predict areal densities sufficient to stop MeV electrons*

Plastic shell: $\rho R \sim 0.45 \text{ g/cm}^2$

e-beam: Gaussian, spot size = 20 $\mu$m (FWHM), duration = 10 ps
angular spread = $20^\circ$ to $60^\circ$ (half angle)
Maxwellian energy spectrum with \( \langle E_h \rangle = 1.2 \) to 2 MeV

Laser pulse: $I_0 = 5.4 \times 10^{19} \text{ W/cm}^2$, $E_\ell = 2.6 \text{ kJ}$
conversion efficiency to hot electrons = 0.3

Hot electrons are collimated by the resistive magnetic field in the integrated simulation.

Snapshots at $t = 6$ ps after the beginning of the e-beam

Plasma density (g/cm$^3$)

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

Azimuthal magnetic field (MG)

$\langle E_h \rangle = 1.6$ MeV
Angular divergence = 20° (half angle)
Hot electrons are collimated for an angular spread as high as 60°

Snapshots at $t = 6$ ps after the beginning of the e-beam

Plasma density (g/cm$^3$)

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

Azimuthal magnetic field (MG)

$\langle E_h \rangle = 1.6$ MeV
Angular divergence = 60° (half angle)
The hot electrons deposit 25% to 75% of their energy on target.
Hot electrons heat up the target by 1 keV (maximum)

Mean hot-electron energy $\langle E_h \rangle = 1.2$ MeV

Neutron yield increases from $3 \times 10^9$ to $1.6 \times 10^{10}$ due to hot electrons

Plasma density (g/cm$^3$)

Plasma temperature increase (keV)
e-beam angular divergence = 20°
e-beam angular divergence = 60°
Summary/Conclusions

Electron-beam collimation by a self-generated resistive magnetic field increases the coupling efficiency of hot electrons with the target and reduces the energy required for ignition.

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