Gain Curves for Fast-Ignition Inertial Confinement Fusion

\[ G_M = \frac{E_{\text{Fusion}}}{E_{\text{Driver}}} \]

\[ G_T = \frac{E_{\text{Fusion}}}{E_{\text{Driver}} + E_{\text{Petawatt}}} \]

A. A. Solodov, R. Betti, J. A. Delettrez, and C. Zhou
Fusion Science Center
Laboratory for Laser Energetics
University of Rochester

48th Annual Meeting of the American Physical Society
Division of Plasma Physics
Philadelphia, PA
30 October–3 November 2006
Gain curves for fast-ignition and ignition requirements have been obtained from hydrodynamic simulations of realistic high-gain, fast-ignition targets.

- Simulations use high-density and high-$\rho R$ fuel assembly recently suggested for fast ignition.*

- A maximum gain curve has been generated for ignition by a collimated monoenergetic electron beam.

- Simulations using Gaussian laser pulses and ponderomotive temperature scaling for fast electrons predict a minimum laser energy for ignition $\geq 100$ kJ for $\lambda_L = 1.05 \, \mu$m.

- A shorter laser wavelength might be necessary to reduce the range of fast electrons to the fuel core size and lower the ignition energy.

Implosion of the high-density and high-\(\rho R\) fuel assembly\(^1\) was simulated using the one-dimensional hydrocode \textit{LILAC}\(^2\)

- Massive cryogenic shells can be imploded with a low-implosion velocity on a low adiabat using a relaxation-pulse technique.\(^3\)
- Such targets are practically unperturbed by the Rayleigh–Taylor instability justifying 1-D simulation of the implosion.

The two-dimensional, two-fluid hydrocode *DRACO*\(^1\) has been recently modified\(^2\) to include electron-beam energy deposition into the dense fuel. A simple straight-line transport model is chosen for relativistic electrons, taking into account (approximately) the effects of multiple scattering and collective plasma oscillations.\(^3\)

Ignition is triggered by a 15-kJ, 2-MeV monoenergetic electron beam in the burn simulation.

Electron-beam radius $r_0 = 20 \, \mu m$ and duration $\tau = 20 \, ps$. 

$300$-kJ fuel assembly
Ion temperature (keV)

$300$-kJ fuel assembly
Density (g/cm$^3$)
High gains are possible with small drivers with energy as low as 200 kJ

\[ G_M = \frac{E_{\text{Fusion}}}{E_{\text{Driver}}} \approx \frac{743}{1 + 30/ E_{\text{Driver}}^{0.33} (\text{kJ})} \]

\[ G_T = \frac{E_{\text{Fusion}}}{E_{\text{Driver}} + E_{\text{Petawatt}}} \]

Using Maxwellian electrons and Gaussian laser pulses increases the energy required for ignition.

Ponderomotive temperature scaling:\(^1\)

\[
\langle E_{\text{hot}} \rangle = \left[ \frac{I(\lambda/1.054 \, \mu\text{m})^2}{10^{19} \, \text{W cm}^{-2}} \right]^{1/2} \text{ MeV}
\]

Electron range:

\[ R = 0.6 \times \langle E_{\text{hot}} \rangle \, \text{g/cm}^2 \]

- \( \langle E_{\text{hot}} \rangle \gg 1 \): Electron range greatly exceeds the optimal range for fast ignition,\(^2\)

\[ R_{\text{opt}} \sim 0.6 \div 1.2 \, \text{g/cm}^2 \]

What is the minimum energy for ignition?

---


\(^2\)S. Atzeni, Phys. Plasmas \textbf{6}, 3316 (1999).
A minimum laser energy for ignition $\geq 100$ kJ for $\lambda_L = 1.05 \mu m$

$\lambda = 1.054 \mu m$

<table>
<thead>
<tr>
<th>$\eta_{PW}$</th>
<th>Minimum PW laser energy (kJ)</th>
<th>Electron-beam energy (kJ)</th>
<th>$\langle E_{hot} \rangle$ (MeV)</th>
<th>E-beam-fuel coupling efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>230</td>
<td>70</td>
<td>7.7</td>
<td>0.68</td>
</tr>
<tr>
<td>0.5</td>
<td>100</td>
<td>50</td>
<td>6.3</td>
<td>0.76</td>
</tr>
</tbody>
</table>

Ignition energy is minimized for $r_0 \approx 25 \mu m$, $\tau \approx 20$ ps.

$E_{\text{laser}} = 230$ kJ, $\eta = 0.3$, $r_0 = 25 \mu m$, $\tau = 20$ ps
Frequency doubling reduces the electron mean energy, stopping length, and the minimum energy for ignition*  

\[ \lambda = 0.527 \, \mu m \]

<table>
<thead>
<tr>
<th>( \eta_{PW} )</th>
<th>Minimum PW laser energy (kJ)</th>
<th>Electron-beam energy (kJ)</th>
<th>( \langle E_{\text{hot}} \rangle ) (MeV)</th>
<th>E-beam-fuel coupling efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>110 (230)</td>
<td>33</td>
<td>3.7</td>
<td>0.93</td>
</tr>
<tr>
<td>0.5</td>
<td>55 (100)</td>
<td>28</td>
<td>3.2</td>
<td>0.99</td>
</tr>
</tbody>
</table>

Ignition energy is minimized for \( r_0 \approx 20 \, \mu m, \tau \approx 15 \) ps.

\[ E_{\text{laser}} = 110 \, \text{kJ}, \eta = 0.3, \quad r_0 = 20 \, \mu m, \tau = 15 \, \text{ps} \]

Summary/Conclusions

Gain curves for fast-ignition and ignition requirements have been obtained from hydrodynamic simulations of realistic high-gain, fast-ignition targets.

• Simulations use high-density and high-$\rho R$ fuel assembly recently suggested for fast ignition.*

• A maximum gain curve has been generated for ignition by a collimated monoenergetic electron beam.

• Simulations using Gaussian laser pulses and ponderomotive temperature scaling for fast electrons predict a minimum laser energy for ignition $\geq 100$ kJ for $\lambda_L = 1.05 \mu$m.

• A shorter laser wavelength might be necessary to reduce the range of fast electrons to the fuel core size and lower the ignition energy.