High-Density and High-$\rho R$
Fuel Assembly for Fast Ignition

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Significant progress has been made in the design of the fuel assembly for fast ignition using low-adiabat, low-velocity implosions.

**Summary**

- A high-yield fuel assembly has been designed; it requires a 750-kJ driver to produce:
  - $\rho R \approx 3 \text{ g/cm}^2$
  - $300 < \rho < 500 \text{ g/cc}$
  - hot-spot volume/total volume $\sim 5\%$ to $7\%$
  - estimated yield $\sim 120 \text{ MJ (if ignited)}$

- A similar cryo target scaled down to 25 kJ yields $\rho > 300 \text{ g/cc}$ and $\rho R \approx 0.8 \text{ g/cm}^2$.

- This method for assembling FI fuel will be first tested through 20-kJ plastic-shell implosions on OMEGA.
Ignition with fast ignition requires a fuel assembly with densities of \(500 > \rho > 300 \text{ g/cc}, \rho R > 0.4 \text{ g/cm}^2\) and small hot-spot volume.

\[ E_{\text{ig}} (kJ) = 11 \left( \frac{400}{\rho (\text{g/cc})} \right)^{1.85} \]

\[ r_{\text{beam}} (\mu m) = 15 \left( \frac{400}{\rho (\text{g/cc})} \right)^{0.95} \]

1 MeV e-stopping \( \rho_s \Delta_s > 0.4 \text{ g/cm}^2 \)

S. Atzeni, Phys. Plasmas 6, 3316 (1999).
High yields with fast ignition require $\rho > 300 \text{ g/cc}$, $\rho R \sim 3 \text{ g/cm}^2$, small hot-spot volume, and gains $> 100$

\[
\text{Gain} = \frac{\eta_h \cdot \theta E_f}{V_i^2 m_{ion}}
\]

\[
\text{Fraction burned} \rightarrow \theta \approx \frac{1}{1 + 7/\rho R}
\]

\[
\text{Hydro-efficiency} \rightarrow \eta_h = \frac{E_{\text{kinetic}}}{E_{\text{Laser}}}
\]
Scaling laws are derived to design targets for integrated FI experiments; low $\alpha$, low-velocity implosions of massive shells yield small hot spots and large areal densities.

\[ \frac{R_{\text{hot spot}}}{\Delta_{\text{stagnation shell}}} \approx 2.1 \left( \frac{V_i (\text{cm/s})}{3 \times 10^7} \right)^{0.96} \]

\[ (\rho R)_{\text{max}} \approx \frac{1.3}{\alpha_{if}} \left[ \frac{E_L (\text{kJ})}{100} \right]^{0.33} \text{g/cm}^2 \]

\[ \rho_{\text{max}} \approx \frac{792}{\alpha_{if}} I_{15}^{0.13} \left[ \frac{V_i (\text{cm/s})}{3 \times 10^7} \right] \text{g/cm}^3 \]

High-gain fuel assemblies for fast ignition can be designed using the scaling formulas

→ Low adiabats enhance densities and areal densities: minimum practical adiabat $\alpha = 0.7$ to 0.8

→ $\rho R(\alpha = 0.7) \approx 3 \Rightarrow E_{\text{Laser}} \approx 750 \text{ kJ}$

→ $\rho_{\text{max}}(\alpha = 0.7) \approx 600 \text{ g/cc} \Rightarrow V_i(\text{cm/s}) \approx 1.7 \cdot 10^7 \text{ cm/s}$

→ $V_i \approx 1.7 \cdot 10^7 \text{ cm/s} \Rightarrow R_h/\Delta_s \sim 1$

High-gain FI target: $E_L = 750 \text{ kJ}$, $\alpha = 0.7$, $V_i \approx 1.7 \cdot 10^7 \text{ cm/s}$

Estimated yield $\sim 120 \text{ MJ}$

In-flight aspect ratio (IFAR) = 18

A high-yield target has been designed for a 750-kJ laser driver.

<table>
<thead>
<tr>
<th>Energy</th>
<th>Implosion velocity</th>
<th>$\alpha$</th>
<th>IFAR</th>
</tr>
</thead>
<tbody>
<tr>
<td>750 kJ</td>
<td>$1.7 \times 10^7$ cm/s</td>
<td>0.7</td>
<td>18</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Maximum averaged density</th>
<th>Peak Density</th>
<th>Maximum $\rho R$</th>
</tr>
</thead>
<tbody>
<tr>
<td>550 g/cc</td>
<td>670 g/cc</td>
<td>3 g/cm$^2$</td>
</tr>
</tbody>
</table>
The 750-kJ capsule is driven by a relaxation laser pulse with a 22-ns main pulse and a contrast ratio of 150.

Can NIF assemble high-gain FI targets? Indirect-drive pulse is 18 ns with a contrast ratio of ~100
The slow implosion velocity leads to negligible Rayleigh–Taylor growth during the laser flat top.

Results from RT postprocessor based on Haan–Goncharov models and NIF laser nonuniformities with 1-THz SSD.

The 750-kJ capsule yields a hot-spot volume < 8% of the compressed volume and a quasi-isochoric density profile.
2-D hydro-simulations of ignition and burn of the 750-kJ target show energy yields $>100$ MJ

Energy yield $\approx 116$ MJ

<table>
<thead>
<tr>
<th>Total beam energy (kJ)</th>
<th>12–20</th>
</tr>
</thead>
<tbody>
<tr>
<td>e-beam radius (μm)</td>
<td>20</td>
</tr>
<tr>
<td>Electron energy (MeV)</td>
<td>2–3</td>
</tr>
</tbody>
</table>

J. A. Delettrez, this conference
Similar targets scaled down to 25 kJ can be assembled on OMEGA yielding high $\rho > 300 \text{ g/cc}$ and $\rho R \approx 0.8 \text{ g/cm}^2$.
This method for assembling FI fuel will be first tested on OMEGA with surrogate plastic-shell implosions.

<table>
<thead>
<tr>
<th>Energy (kJ)</th>
<th>Implosion velocity ($\mu$m/s)</th>
<th>Maximum $\rho R$ (5–15 atm)</th>
<th>Maximum $\rho$ (5–15 atm)</th>
<th>Proton yield (5–15 atm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>1.2</td>
<td>2.1 $\cdot 10^7$ cm/s</td>
<td>0.5–0.36 g/cm$^2$</td>
<td>276–190 g/cc</td>
</tr>
</tbody>
</table>
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