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 25-kJ capsule can be assembled on the OMEGA laser to achieve
  - $\rho R \approx 0.8 \text{ g/cm}^2$, $300 < \rho < 500 \text{ g/cc}$
  - hot-spot volume/total volume $< 15\%$
- Planned plastic–shell implosion experiments on OMEGA are expected to achieve $\rho R \approx 0.3–0.5 \text{ g/cm}^2$ and $\rho \approx 200–300 \text{ g/cc}$.
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.

$\Delta T = \frac{3}{1 + \rho T S}$

$\Delta T = \frac{H_D N_D}{F_B N_B}$

$\rho T H D D F m S C F B N / E k g c 11400. i g 185 = \rho^h h; E / g c m 04 s s 2 \rho D 1 \text{MeV} e\text{-stopping} / r g c c 15400. beam 095 = \rho^h h; E (m m)$

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

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

$1 \text{ MeV} e\text{-stopping} \, \rho S \, \Delta s > 0.4 \, \text{g/cm}^2$

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 $> 100$

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

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

**Hydro-efficiency** \[ \eta_h = \frac{E_{\text{kinetic}}}{E_{\text{Laser}}} \]

**Gain equation** \[ \text{Gain} = \frac{73}{I_{15}^{0.25}} \left( \frac{3 \cdot 10^7}{V_i} \right)^{1.25} \left( \frac{\theta}{0.2} \right) \]

\[ 0.049 \left( \frac{V_i (\text{cm/s})}{I_{15}^{0.25}} \right)^{0.75} \]

$\eta_h$ vs. $\frac{V_i (\text{cm/s})}{I_{15}^{0.25}}$
Scaling laws relating stagnation to in-flight hydro-variables are derived from conservation equations.

\begin{align*}
(1) \text{Mass} \rightarrow & \quad \rho_s \Delta_s \sim \frac{M_{sh}}{R_h \Sigma(A_s)} \sim \frac{E_K}{R_h V_i \Sigma(A_s)} \\
(2) \text{Energy} \rightarrow & \quad E_K \sim P_s (R_h + \Delta_s)^3 \\
(3) \text{Entropy} \rightarrow & \quad \alpha_s \sim \alpha_{if} \text{Mach}_{if}^{2/3}
\end{align*}

\( A_s \equiv \frac{R_h}{\Delta_s} \quad \leftarrow \text{Stagnation aspect ratio} \)

\( \Sigma(x) \equiv 1 + \frac{1}{x} + \frac{1}{(3x^2)} \quad \leftarrow \text{Volume factor} \)

\( \alpha_{if} \equiv \text{in-flight adiabat} \)

Unknowns \( \rightarrow \) \( P_s, \rho_s, A_s, \Delta_s \)
Simulations of optimized implosions (max \( \rho R \) and \( \rho \)) yield a scaling relation for the stagnation aspect ratio.
The areal density is weakly dependent on velocity; it increases for lower adiabats and greater energies.

\[(\rho_s \Delta_s)^{\text{theory}} \sim E_L^{0.33} V_i^{0.03} \alpha_{if}^{-0.8}\]

\[(\rho R)_{\text{max}} = \frac{1.3}{\alpha_{if}^{0.55}} \left[ \frac{E_L (\text{kJ})}{100} \right]^{0.33} \left[ \frac{V_i (\text{cm/s})}{3 \cdot 10^7} \right]^{0.06}\]
The density is independent of energy; it increases with the velocity and decreases with the adiabat. 

\[ \rho_s^{\text{theory}} \sim V_i^{1.4} I_L^{0.13} \alpha_{if}^{-1.2} \]

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

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

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

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

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

Estimated yield $\sim 120$ MJ

In-flight aspect ratio (IFAR) = 18

For a fixed minimum adiabat and fixed peak density, the gain (without PW) depends only on the driver energy $E_L$.

$$V_I (\text{cm/s}) = \frac{1.7 \times 10^7 \left( \frac{\rho_{\text{max}}}{600} \right) \left( \frac{\alpha_{\text{if}}}{0.7} \right)}{I_{15}^{0.13}}$$

$$\xi = 0.5, \quad \xi = 1$$

$$\xi = \text{fraction of } (\rho R)_{\text{max}} \text{ available for burn}$$
A high-yield target has been designed for a 750-kJ laser driver.

<table>
<thead>
<tr>
<th>Energy</th>
<th>Implosion velocity</th>
<th>α</th>
<th>IFAR</th>
</tr>
</thead>
<tbody>
<tr>
<td>750 kJ</td>
<td>1.7 \cdot 10^7 cm/s</td>
<td>0.7</td>
<td>18</td>
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<table>
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<tr>
<th>Maximum averaged density</th>
<th>Peak Density</th>
<th>Maximum (\rho R)</th>
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<tr>
<td>550 g/cc</td>
<td>670 g/cc</td>
<td>3 g/cm²</td>
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Using the relaxation-type laser pulse leads to improved hydrostability and a lower laser–power contrast ratio.

\[ P_{\text{foot}}^{(\text{Mb})} \approx 2 \alpha_{\text{if}} \]

\[ P_{\text{foot}}^{(\text{Mb})} \approx 6 \alpha_{\text{if}} \]

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 750-kJ capsule yields a hot-spot volume < 8% of the compressed volume and a quasi-isochoric density profile.
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.

2-D hydro-simulations of ignition and burn of the 750-kJ target show energy yields >100 MJ

Energy yield ≈ 116 MJ

<table>
<thead>
<tr>
<th>Total beam energy (kJ)</th>
<th>12–20</th>
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<tbody>
<tr>
<td>e-beam radius (µm)</td>
<td>20</td>
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<tr>
<td>Electron energy (MeV)</td>
<td>2–3</td>
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*J. A. Delettrez, this conference*
The relatively cold hot spot of such fuel assemblies can also be ignited by a spherically convergent shock*.

Target yield from 1-D hydro-simulation: 118 MJ

*C. Zhou, this conference.
A 25-kJ driver can assemble fuel for fast ignition using low-adiabat implosions of thick shells with a pulse compatible with the OMEGA Laser System.

<table>
<thead>
<tr>
<th>Energy</th>
<th>IFAR</th>
<th>$\alpha$</th>
</tr>
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<tbody>
<tr>
<td>25 kJ</td>
<td>30</td>
<td>1</td>
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<table>
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<tr>
<th>Implosion velocity</th>
<th>Maximum density</th>
<th>Maximum $\rho R$</th>
</tr>
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<tbody>
<tr>
<td>$2.6 \times 10^7$ cm/s</td>
<td>700 g/cc</td>
<td>0.8 g/cm$^2$</td>
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</table>
The 130-μm capsule is driven by a relaxation laser pulse within the capabilities of the OMEGA laser.

- Main pulse length = 3.5 ns
- Prepulse width = 70 ps
- Prepulse/main = 0.4
- Main contrast ratio = 32
- Pulse energy = 25 kJ
- Peak power = 20 TW
The 130-μm, $\alpha = 1$, OMEGA-compatible capsule yields a density $> 300$ g/cc over a $\rho R > 0.4$ g/cm$^2$ and a hot-spot volume $< 20\%$ of the total volume.
This method for assembling FI fuel will be first tested on OMEGA with surrogate plastic-shell implosions.

Energy | $\alpha$ | Implosion velocity | Maximum $\rho R$ (5–15 atm) | Maximum $\rho$ (5–15 atm) | Proton yield (5–15 atm) |
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<tr>
<td>20 kJ</td>
<td>1.2</td>
<td>$2.1 \times 10^7$ cm/s</td>
<td>0.5–0.36 g/cm$^2$</td>
<td>276–190 g/cc</td>
<td>1.2–2.3 $\times 10^8$</td>
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