Fast-Ignition Fuel Assembly: Theory and Experiments

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Summary

Scaling laws for fast-ignition fuel assembly are derived and used to design high-density and high-areal-density implosions

• High-density and high-areal-density capsules are optimized for fast-ignition implosions.

• Density depends on adiabat and implosion velocity. It is independent of driver energy.

• Areal density depends on adiabat and driver energy, and depends weakly on implosion velocity.

• Hot-spot temperature depends only on the implosion velocity.

• Low-adiabat, low-implosion-velocity cryogenic implosions on OMEGA can achieve areal densities up to 0.78 g/cm².
Energy gain increases for low-implosion velocity and high areal density.

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

\[ \theta = \frac{1}{1 + 7/\rho R} \text{ = fraction burned} \]

\[ m_i = \text{ion mass} \]

\[ E_f = 17.5 \text{ MeV} \]

\[ \eta_h = \text{hydrodynamic efficiency} \]

Gain formula \( \Rightarrow \)

\[ G = \frac{73}{I_{15}^{0.25}} \left( \frac{3 \times 10^7}{V_i} \right)^{1.25} \left( \frac{\theta}{0.2} \right) \]

- Higher \( \rho R \) \( \rightarrow \) longer confinement time
- Lower \( V_i \) \( \rightarrow \) more fuel mass for the same kinetic/laser energy
Scaling laws relating stagnation properties to in-flight hydrodynamic variables are derived from conservation equations.

Hot-spot ignition

\[ P = P_{hs} = P_s \]

\[ P_s \Delta_s \sim \frac{\rho_s}{\rho_h} \frac{M_{sh}^2}{R_h^2 \Sigma(A_s)} \sim \frac{E_k}{R_h^2 V_i^2 \Sigma(A_s)} \]

Energy:

\[ E_k \sim P_s (R_h + \Delta_s)^3 \]

Entropy:

\[ \alpha_s \sim \alpha_{if} \text{Mach}_{if}^{2/3} \]

Fast ignition

\[ P = P_{hs} = P_s \]

Aspect ratio:

\[ A_s = \frac{R_h}{\Delta_s} \]

Volume factor:

\[ \Sigma(x) \equiv 1 + \frac{1}{x} + \frac{1}{3x^2} \]

Unknowns:

\[ P_s, \rho_s, A_s, \Delta_s \]

The stagnation aspect ratio decreases with lower implosion velocity.

\[ A_s^{\text{sim}} = \frac{R_h}{\Delta_s} \]

\[ A_s^{\text{fit}} = 2.1 \left( \frac{V_i (\text{cm/s})}{3 \times 10^7} \right)^{0.96} \]
The hot-spot temperature decreases with lower velocity

$$T_{\text{hot spot}}^{\text{fit}} \,(\text{keV}) = 7 \left( \frac{V_i \, (\text{cm/s})}{3 \times 10^7} \right)^{1.4} \alpha^{-0.04}$$
The areal density is dependent on adiabat and driver energy

\[ (\rho R)^{\text{theory}} \sim E_L^{0.33} \alpha_f^{-0.8} V_I^{0.03} \]

\[ (\rho R)^{\text{fit}} = \frac{1.2}{\alpha^{0.57}} \left( \frac{E_L \text{(kJ)}}{100} \right)^{0.33} \left( \frac{V_i \text{(cm/s)}}{3 \times 10^7} \right)^{0.1} \]

Fast ignition requires large enough densities; the density depends on velocity and adiabat.

\[ \rho_s^{\text{theory}} \sim V_I^{1.4} \alpha_{if}^{-1.2} \]

[Graph showing a linear relationship between \( \langle \rho \rangle \rho R \) and \( \langle \rho R \rangle^{\text{fit}} \rho R \), with the formula given by:]

\[ \langle \rho R \rangle^{\text{fit}} \rho R = \frac{440}{\alpha^{1.03}} \left( \frac{V_i (\text{cm/s})}{3 \times 10^7} \right)^{0.93} \]

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The hydrodynamics of fast ignition depend on three parameters: gain, density, and areal density.

\[
\text{Gain} \sim V_i^{-1.25} \left( 1 + 7 / \rho R \right)^{-1} \Rightarrow \frac{743}{1 + 30 E_L^{1/3}} \text{(kJ)}
\]

\[
\rho R \sim E_L^{0.33} / \alpha^{0.57}
\]

\[
\rho \sim V_i / \alpha
\]

- Fast-ignition implosion
  - low-velocity \( V_i \)
  - low-adiabat \( \alpha \)
  - large mass

\[
E_{ig}^* (kJ) \approx 11 \left[ \frac{400}{\rho (g/cc)} \right]^{1.95}
\]

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

High \( \rho \) is required for fast ignition

Upper bound of the density

*S. Atzeni, Phys. Plasmas 6, 3316 (1999).*
Low-adiabat implosions lead to high $\rho$ and $\rho R$ with low velocities, large masses, and high gains

**Implosion Characteristics**

- Choose the lowest possible adiabat. Limitation to the minimum adiabat comes from the laser pulse length and the pulse contrast ratio; $\alpha = 0.7$ seems a reasonable value
- Choose stagnation density
- Find the implosion velocity from the density equation

**Target Design**

- Set $I \approx 10^{15}$ W/cm$^2$
- Choose driver energy and corresponding laser power
- Find capsule outer radius from power and intensity
- Find final mass from kinetic energy
- Assuming a 20% ablated mass leads to an initial mass
- Initial mass and outer radius yield the inner radius
Optimized fast-ignition cryo targets are thick shells of wetted foam with an initial aspect ratio of ~2

These targets have high areal densities and low IFAR

Low-adiabat implosions are driven by RX laser pulses.
The 750-kJ capsule yields a density >300 g/cc over a $\rho R > 2$ g/cm$^2$

The hot-spot volume is <8% of the compressed volume.
Low-adiabat, low-$V_i$ implosions of surrogate CH targets are used to study fast-ignition fuel assemblies on OMEGA.

$E_L \approx 20 \text{ kJ}, \alpha \approx 1.3, V_i \approx 2 \cdot 10^7 \text{ cm/s}$

<table>
<thead>
<tr>
<th>Pressure (atm)</th>
<th>$\rho$ (g/cc)</th>
<th>$2\rho R$ (g/cm$^2$)</th>
<th>$E_{\text{stop}}$ (MeV)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>35</td>
<td>89.3</td>
<td>0.52</td>
<td>2.10</td>
</tr>
<tr>
<td>25</td>
<td>101</td>
<td>0.62</td>
<td>2.35</td>
</tr>
<tr>
<td>15</td>
<td>120</td>
<td>0.74</td>
<td>2.76</td>
</tr>
<tr>
<td>5</td>
<td>185</td>
<td>1.02</td>
<td>3.53</td>
</tr>
<tr>
<td>1</td>
<td>222</td>
<td>1.32</td>
<td>4.45</td>
</tr>
</tbody>
</table>

The DD neutron production begins as predicted and shows a 200-ps truncation, probably due to hot-spot CH–DD mixing.

D₂ 25 atm
Shot # 43075
\( E_L = 20.5 \text{ kJ} \)
No SSD

YOC = 3%
The measured\textsuperscript{1} and reconstructed\textsuperscript{2} downshifted secondary proton spectra are in good agreement.

The reconstruction used the measured neutron rate and the simulated $\rho R(t)$.

- Measured spectrum
- LILAC with 1-D source size
- LILAC with point source
- LILAC averaged

\begin{align*}
\langle \rho R \rangle_{\text{max}} &= 0.26 \text{ g/cm}^2 \\
\langle \rho R \rangle_n &= 0.15 \text{ g/cm}^2
\end{align*}

\textsuperscript{1}F. H. Séguin et al., Rev. Sci. Instrum. 74, 975 (2003).
\textsuperscript{2}P. B. Radha et al., APS/DPP 2006 (GO2.00008).
The $\langle \rho R \rangle$ modulations are <10%, indicating that the compressed core is not significantly affected by low-mode ($\ell \leq 5$) nonuniformities.

D$_2$ 25 atm
Shot 43075
$E_L = 20.5$ kJ
No SSD
The measured\(^1\) and reconstructed\(^2\) downshifted primary proton spectra are in good agreement for \(\text{D}^3\text{He}\) implosions.

\[\text{D}^3\text{He 25 atm} \]

\[\text{Shots 43110 & 43113} \]

\[E_L = 20.5 \text{ kJ} \]

\[\text{no SSD} \]

\[\text{14.7 MeV birth energy} \]

\[6.5 \text{ MeV} \]

The calculation used an estimated proton rate and the simulated \(\rho R\) evolution.

- Measured spectrum
- Calculated spectrum

\[8.2\text{-MeV downshift} \]

\[\langle \rho R \rangle_{\text{max}} = 0.24 \text{ g/cm}^2 \]

\[\langle \rho R \rangle_n = 0.13 \text{ g/cm}^2 \]


\(^2\)P. B. Radha et al., APS/DPP 2006 (GO2.00008).
Very good agreement between measured and predicted areal densities is obtained.

<table>
<thead>
<tr>
<th>Shot number</th>
<th>Gas fill</th>
<th>Pressure (atm)</th>
<th>Measured $\langle \rho R \rangle_p$</th>
<th>Sim. shell $\langle \rho R \rangle_n$</th>
<th>Measured $\rho R_n^{\text{max}}$</th>
<th>Sim. $\rho R_n^{\text{max}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>43074</td>
<td>$D_2$</td>
<td>34</td>
<td>0.133</td>
<td>0.138</td>
<td>0.25</td>
<td>0.24</td>
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<tr>
<td>43075</td>
<td>$D_2$</td>
<td>25</td>
<td>0.146</td>
<td>0.144</td>
<td>0.26</td>
<td>0.26</td>
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<tr>
<td>43107</td>
<td>$D_2$</td>
<td>25</td>
<td>0.122</td>
<td>0.132</td>
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<td>0.27</td>
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<tr>
<td>43114</td>
<td>$D_2$</td>
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<td>0.112</td>
<td>0.23</td>
<td>0.23</td>
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<tr>
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<td>$D_2$</td>
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<td>0.128</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>43108</td>
<td>$D_2$</td>
<td>13</td>
<td>0.129</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>43109 + 43112</td>
<td>$D^3\text{He}$</td>
<td>33</td>
<td>0.128</td>
<td>—</td>
<td>0.24</td>
<td>0.25</td>
</tr>
<tr>
<td>43110 + 43113</td>
<td>$D^3\text{He}$</td>
<td>25</td>
<td>0.130</td>
<td>—</td>
<td>0.24</td>
<td>0.28</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td></td>
<td></td>
<td><strong>0.131</strong></td>
<td><strong>0.132</strong></td>
<td><strong>0.24</strong></td>
<td><strong>0.25</strong></td>
</tr>
</tbody>
</table>