Fast-Ignition Fuel Assembly

Hot-spot ignition

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

- \( T_i \)
- \( R_h \)
- \( \rho_h \)
- \( \rho_s \) shell
- \( \Delta_s \)
- \( R_s \)

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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

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

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

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

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

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

Gain formula \( \Rightarrow \)

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

\[ \eta_h^{\text{theory}} \sim V_i^{0.87} I_L^{-0.29} \]

\[ \eta_h^{\text{fit}} = \frac{0.049}{I_{15}^{0.25}} \left( \frac{V_i (\text{cm/s})}{3 \times 10^7} \right)^{0.75} \]
Scaling laws relating stagnation properties to in-flight hydrodynamic variables are derived from conservation equations.

**Hot-spot ignition**

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

\[ \begin{align*} 
    T_i & \quad \rho_s \Delta_s \\
    R_h & \quad \Delta_s \\
    \rho_h & \quad R_s
\end{align*} \]

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

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

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

**Fast ignition**

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

\[ \begin{align*} 
    T_i & \quad \rho_s \Delta_s \\
    R_h & \quad \Delta_s \\
    \rho_h & \quad R_s
\end{align*} \]

**Aspect ratio:**
\[ A_s = \frac{R_h}{\Delta_s} \]

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

**Unknowns:**
\[ P_s, \rho_s, A_s, \Delta_s \]

*R. Betti et al., Phys. Plasmas 9, 2277 (2002).*
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

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

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

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

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

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

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

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

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

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

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

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

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

\[
r_{\text{beam}}^* \text{(\( \mu \text{m} \))} = 15 \left[ \frac{400}{\rho \text{ (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 $\sim 2$.

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.
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