Shock Ignition of Thermonuclear Fuel with High-Areal Density

$E_L = 400$ to $500$ kJ

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Optimal targets for shock ignition are thick shells driven on a low adiabat at low implosion velocities (and low IFAR ~20)

- A convergent shock launched by a spike in the laser intensity leads to an adiabatic compression of the hot spot and reduction of the energy required for ignition.

- The robustness of the SI scheme is measured by the size of the shock-launching-time ignition window.

- 2-D simulations indicate that shock ignition may survive the detrimental effects of laser imprinting at a relatively low driver energy (~400 to 500 kJ) leading to gains of ~50 to 80.

- Applications of SI to the NIF in following talk U02.00011 by L. J. Perkins

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Collaborators

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High areal densities ($\rho R$) and low-implosion velocities ($V_i$) lead to high-energy gains (assuming that ignition occurs)

$$G = \frac{E_{\text{fusion}}}{E_{\text{laser}}} \sim \frac{\theta}{V_i^{1.2}}$$

$$\theta = \frac{1}{1 + \frac{7}{\rho R}} = \text{burnup fraction}$$

- Higher $\rho R \rightarrow$ longer burn time
- Lower $V_i \rightarrow$ more fuel mass for the same kinetic/laser energy
The hot-spot ignition condition is given by the balance of alpha heating with energy losses, including expansion losses.

\[
\frac{\dot{E}_{hs}}{E_{hs}} = \frac{1}{\tau_{\alpha}} - \frac{1}{\tau_{\text{rad}}} - \frac{1}{\tau_{\exp}} > 0
\]

\[
1/\tau_{\alpha} \sim n_{hs}^2 \langle \sigma v \rangle / P_{hs} \quad \text{alpha heating}
\]

\[
1/\tau_{\text{rad}} \sim n_{hs}^2 \sqrt{T_{hs}} / P_{hs} \quad \text{radiation cooling}
\]

\[
1/\tau_{\exp} \sim \sqrt{\dot{R}_{hs}/R_{hs}} \quad \text{expansion}
\]

\[
M_s \dot{R}_{hs} = 4\pi P_{hs} R_{hs}^2 \quad \text{shell Newton’s law}
\]
For isobaric fuel assemblies, the ignition condition depends only on velocity and shell areal density.

\[
(p_s \Delta_s)^2 V^2 (T_{\text{keV}}^{\text{isob}} - 4.4) > \text{const}
\]

- \(V_{\text{min}}\) is the minimum velocity required to overcome radiative losses \(\sim 1.5 \times 10^7\) cm/s.

For \(V \gg V_{\text{min}}\)

\[
(p_s \Delta_s)^2 V^2 \left( \frac{V}{V_{\text{min}}} \right)^{1.4} - 1 > \text{const}
\]

\[
T_{\text{max}}^{\text{hot spot (keV)}} = 7 \left[ \frac{V_i (\text{cm/s})}{3 \times 10^7} \right]^{1.4}
\]

Ignition requirements set a threshold for the shell areal density.
The ignition condition can be modified to include the effect of a non-isobaric fuel assembly

\[
\hat{\phi} \left( \rho_s \Delta_s \right)_{\text{iso}}^2 V^2 \left( \phi^{0.3} \left( \frac{V}{V_{\text{min}}} \right)^{1.4} - 1 \right) > \text{const}
\]

Shell areal density \( P_{\text{hs}} \) and implosion velocity \( V \)

Non-isobaric enhancement

\[
\hat{\phi} \equiv \frac{P_{\text{hs}}/R_{\text{hs}}}{P_{\text{iso}}/R_{\text{iso}}}
\]
The areal density depends on energy and adiabat.

\[
(\rho\Delta)_{\text{max}}^{\text{fit}} = \frac{1.2}{\alpha^{0.57}} \left( \frac{E_L \text{ (kJ)}}{100} \right)^{0.33} \left( \frac{V \text{ (cm/s)}}{3 \times 10^7} \right)^{0.1} \text{g/cm}^2
\]

C. Zhou, BO3.00003
The ignition threshold can be lowered in non-isobaric fuel assemblies.

\[ E_{\text{ign}}^{\text{min}} = \text{const} \times \frac{\alpha^{1.8}}{\sqrt{5.4}} \frac{1}{\dot{\phi}^2} + E_{\text{non-isob}} \]

Recover Herrmann et al. scaling for \( \dot{\phi} = 1 \), \( E_{\text{non-isob}} = 0 \)

\[ \dot{\phi}^2 \sim \left( \frac{P_{\text{hs}}/R_{\text{hs}}}{P_{\text{iso}}/R_{\text{iso}}} \right)^2 \sim \left( \frac{R_{\text{iso}}}{R_{\text{hs}}} \right)^{12} \]

For adiabatic compression of the hot spot

Large improvements for small reductions of the hot-spot radius.

Non-isobaric enhancement is achieved through a convergent shock; the ignitor shock is launched by a spike of the laser intensity.

\[ E_L = 400 \text{ to } 500 \text{ kJ}, \quad V_i = 2.4 \times 10^7 \text{ cm/s}, \quad \alpha = 0.7 \text{ to } 1.0 \]

IFAR \approx 18

Minimum shock energy for ignition = 50 kJ
The shock resulting from the collision of the ignitor and return shock compresses the hot spot.
The shock-induced compression of the hot spot is adiabatic; the ignition condition is improved.

The shock compression is adiabatic

\[ P_{\text{shock}} = P_{\text{no shock}} \left( \frac{R_{\text{no shock}}}{R_{\text{shock}}} \right)^5 \]

\[ P_{\text{shock}} = 720 \text{ Gbar} \]

Non-isobaric enhancement

\[ \phi^2 = 7 \]

Reduction of the energy required for ignition for a “free” shock
The robustness of the ignition is measured by the size of the shock-ignition window.
Summary/Conclusions

Optimal targets for shock ignition are thick shells driven on a low adiabat at low-implosion velocities (and low IFAR ~20)

- A convergent shock launched by a spike in the laser intensity leads to an adiabatic compression of the hot spot and reduction of the energy required for ignition.
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Hot electrons with energies $< 100 \text{ keV}$ slow down on the shell’s outer surface.