Effects of Long- and Intermediate-Wavelength Asymmetries on Hot-Spot Energetics

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Summary

Low and intermediate-mode nonuniformities lead to different degradation mechanisms of inertial confinement fusion (ICF) implosion performance

- Low-mode ($\ell \sim 2$) asymmetries show a drop in hot-spot pressure while the hot-spot volume is unchanged
- Intermediate-mode ($\ell \sim 10$) asymmetries result in a smaller hot-spot volume, while the pressure is not significantly degraded
- Large-amplitude intermediate modes exhibit a “secondary-piston effect,” allowing for a secondary conversion of the shell’s kinetic energy to hot-spot internal energy
- The signatures of single-mode nonuniformities can provide physical insight into the understanding of implosion results
Collaborators

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Implosion performances are quantified using the following hydrodynamic and burn parameters:

- **Yield** ($Y$), neutron rate ($\dot{Y}$) and burnwidth ($\tau$):

  \[ Y = \int dt \int dV \frac{n^2 \langle \sigma v \rangle}{4} \rightarrow \dot{Y} = \int dV \frac{n^2 \langle \sigma v \rangle}{4} \]

- Neutron-averaged quantities: Temperature ($T$), and pressure ($P$)

  \[ \langle Q \rangle = \frac{\int dt \int dV \frac{n^2 \langle \sigma v \rangle}{4} Q}{Y} \]

- **YOC** $\equiv \left( \frac{Y \text{ from experiments or 3-D/2-D simulations}}{Y \text{ from 1-D simulations}} \right)$

- **Burn volume** ($V$)

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*YOC: yield over clean

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A new definition for the burn volume is introduced, it is the volume of the confined plasma that produces neutrons.

\[ V = \frac{\int dt \left( \int dV \frac{n^2 \langle \sigma v \rangle}{4} \right)^2}{\int dt \int dV \left( \frac{n^2 \langle \sigma v \rangle}{4} \right)^2} \]

- The burn volume is an essential simulation diagnostic to explain neutron yields.
The effect of instabilities are studied by rewriting the yield in terms of the hot-spot quantities

- **Yield:** \( Y \sim P^2 \frac{\langle \sigma v \rangle}{T^2} V \tau \)

- The temperature dependence of the fusion reactivity in the range of \( 2 < T < 7 \) keV follows:* 
  \[
  \frac{\langle \sigma v \rangle}{T^2} \sim T^{1.72}
  \]

- The yield and YOC can be written as 
  \( Y \sim P^2 T^{1.7} V \tau \)

\[
YOC \backsimeq \left( \frac{P_{3-D}}{P_{1-D}} \right)^2 \left( \frac{V_{3-D}}{V_{1-D}} \right) \left( \frac{T_{3-D}}{T_{1-D}} \right)^{1.7} \left( \frac{\tau_{3-D}}{\tau_{1-D}} \right)
\]

*R. Betti et al., Phys. Plasmas 17, 058102 (2010).*
The radiation–hydrodynamic code **DEC2D/3D** is used to simulate the deceleration phase of implosions.

- This is a Eulerian code with a moving mesh that shrinks radially to maintain high resolution during the compression.
- Hydrodynamic-profiles at the end of the acceleration phase (from the 1-D code **LILAC**) are used as the starting point, followed by a simulation of the deceleration phase in multidimension.
- Single-or multimode velocity perturbations are introduced to the inner surface of the shell.

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OMEGA and extrapolated ignition targets show similar trends; therefore, the analysis is applicable to both scales.

- Low modes ($1 \leq \ell \leq 5$) arise mainly because of target offset**
- Intermediate modes ($5 \leq \ell \leq 60$) can arise because of multiple effects, including surface defects***
- Some intermediate modes ($\ell \sim 10$ and $\ell \sim 18$) can be seeded in excess by the overlap intensity arising from the beam geometry**

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Single-mode nonuniformities have a distinct effect on the shape of the fuel and hot spot.
While intermediate-$\ell$ modes exhibit yield degradation caused primarily by a drop in volume, low-$\ell$ modes show no reduction in volume.

\[
YOC \approx \left( \frac{P}{P_{1-D}} \right)^2 \left( \frac{V}{V_{1-D}} \right) \left( \frac{T}{T_{1-D}} \right)^{1.7} \left( \frac{\tau}{\tau_{1-D}} \right)
\]
Yield degradation from low-$\ell$ modes result from a significant reduction in pressure compared to the 1-D value.

\[
\text{YOC} \approx \left( \frac{P}{P_{1-D}} \right)^2 \left( \frac{V}{V_{1-D}} \right) \left( \frac{T}{T_{1-D}} \right)^{1.7} \left( \frac{\tau}{\tau_{1-D}} \right)
\]
Rayleigh–Taylor spike convergence results in an increase in the central pressure for intermediate-$\ell$ modes even when the YOC decreases: secondary piston

- Residual shell kinetic energy for low mode $\sim 200$ J
- Secondary conversion of shell kinetic energy to hot-spot internal energy for intermediate mode $\sim 200$ J
Three-dimensional simulations with single mode ($\ell = 10, m = 10$) confirm the “secondary-piston” effect.

Central region with $P \sim 150$ Gbar (higher than unperturbed $P \sim 110$ Gbar)

At peak neutron rate

$\rho$ (g/cm$^3$)

0

200

400

P (Gbar)

0

75

150

Ion temperatures are little affected by nonuniformities up to yield degradations of $\sim 50\%$.

\[
\text{YOC} \approx \left( \frac{P}{P_{1-D}} \right)^2 \left( \frac{V}{V_{1-D}} \right) \left( \frac{T}{T_{1-D}} \right)^{1.7} \left( \frac{\tau}{\tau_{1-D}} \right)
\]
Burnwidths are reduced only for intermediate-\(\ell\) modes because of the secondary-piston effect.

The burn widths are comparable for YOC > 0.6

\[
\text{YOC} \approx \left( \frac{P}{P_{1-D}} \right)^2 \left( \frac{V}{V_{1-D}} \right) \left( \frac{T}{T_{1-D}} \right)^{1.7} \left( \frac{\tau}{\tau_{1-D}} \right)
\]
The understanding can be extended to explain trends in results with multimode nonuniformities.

**Clean**

**Multimode**

With superposition of low modes and intermediate \( \ell = 10 \) mode.
Multimode simulations can be explained by superposing the trends shown by low and intermediate modes.
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