The Physics of Low- and Mid-Mode Asymmetries of the Hot Spot

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The neutron-averaged observables can differ from the hot-spot volume-averaged quantities; the differences although small for low modes are more pronounced for mid-mode asymmetries

- The asymmetries are divided into low and mid modes by comparison of the mode wavelength with the hot-spot radius
- Low modes introduce nonradial motion, whereas mid modes involve cooling by thermal losses
- The energy distribution at stagnation is similar for both asymmetry types; however, the fusion reaction distribution is different
- A general expression is found relating the pressure degradation to the residual shell energy and the flow within the hot spot (i.e., the total residual energy)

Summary

Collaborators

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The radiation–hydrodynamic code \( \text{DEC2D}^* \) is used to simulate the deceleration phase of implosions.

Simulation Technique

\[ \text{V}_{\text{imp}} \approx 380 \text{ km/s} \]

\[ r \approx 90 \mu m \]

\[ r \approx 22 \mu m \]

\[ \Delta V / V_{\text{imp}} \]

\[ N \text{LAC}^\dagger \]

\[ \text{DEC2D}^* \]

\[ \text{DT ice} \]

\[ \text{DT gas} \]

\[ 430 \mu m \]

\[ 8 \mu m \]

\[ 50 \mu m \]

\[ 77068 \text{ (26.18 kJ)} \]

\[ 77064 \text{ (26.12 kJ)} \]

\[ P_{\text{shape}} \]

\[ \text{Power (TW)} \]

\[ \text{Time (ns)} \]

\[ N \text{LAC}^\dagger \]

\[ \text{DEC2D}^* \]

\[ \text{Stagnation} \]

\[ \Delta V / V_{\text{imp}} \]

\[ 77068 \text{ (26.18 kJ)} \]

\[ 77064 \text{ (26.12 kJ)} \]

\[ 5 \text{ TW} \]

\[ 10 \text{ TW} \]

\[ 15 \text{ TW} \]

\[ 20 \text{ TW} \]

\[ 25 \text{ TW} \]

\[ 0 \text{.0} \]

\[ 0.5 \text{.0} \]

\[ 1.0 \text{.0} \]

\[ 1.5 \text{.0} \]

\[ 2.0 \text{.0} \]

\[ 2.5 \text{.0} \]

\[ 3.0 \text{.0} \]

\[ 0 \text{.0} \]

\[ 5 \text{.0} \]

\[ 10 \text{.0} \]

\[ 15 \text{.0} \]

\[ 20 \text{.0} \]

\[ 25 \text{.0} \]

\[ 26.18 \text{ kJ} \]

\[ 26.12 \text{ kJ} \]


\[ A. \text{Bose et al., Phys. Plasmas 22, 072702 (2015).} \]

\[ \text{Nonlocal + cross-beam energy transfer model:} \]

\[ \text{I. V. \text{Igumenshchev et al.}, Phys. Plasmas 17, 122708 (2010).} \]
The observables for cryogenic implosions on OMEGA* can be reproduced using a combination of low and mid modes**

Motivation

For indirect-drive implosions on the NIF, low modes are considered to be the main cause of degradation†

<table>
<thead>
<tr>
<th></th>
<th>Experiment</th>
<th>2-D simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E_L ) (kJ)</td>
<td>26.18 ( \times 10^{13} ) (±5%)</td>
<td>5.3 ( \times 10^{13} )</td>
</tr>
<tr>
<td>( \text{Yield} )</td>
<td>5.3 ( \times 10^{13} ) (±5%)</td>
<td>5.3 ( \times 10^{13} )</td>
</tr>
<tr>
<td>( P ) (Gbar)</td>
<td>56 (±7)</td>
<td>56</td>
</tr>
<tr>
<td>( T_i ) (keV)</td>
<td>3.6 (±0.3)</td>
<td>3.7</td>
</tr>
<tr>
<td>( R_{\text{hs}} ) (( \mu )m)</td>
<td>22 (±1)</td>
<td>22</td>
</tr>
<tr>
<td>( \tau ) (ps)</td>
<td>66 (±10)</td>
<td>54</td>
</tr>
<tr>
<td>( \rho R ) (g/cm²)</td>
<td>0.196 (±0.018)</td>
<td>0.194</td>
</tr>
</tbody>
</table>

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NIF: National Ignition Facility
For low-mode asymmetries the bubbles are hot and sustain fusion reactions, while for mid modes they are cooled by thermal losses.

- **Low mode** ($\lambda_{RT} > R_h$)
  - bubbles are hot and sustain fusion
  - hot spot is isobaric (approximately)
  - nonradial flow motion in the shocked shell and hot spot

- **Mid mode** ($\lambda_{RT} < R_h$)
  - bubbles are cold and do not produce fusion
  - hot spot is not isobaric $\nabla P \sim \text{Mach}^2$
  - radially inward and outward motion
For implosions with asymmetries, the neutron-averaged and the volume-averaged quantities are different, but the differences are less for low modes and more pronounced for mid modes.

\[
Q_n = \frac{\int dt \int dV n_T \langle \sigma v \rangle Q}{\int dt \int dV n_T \langle \sigma v \rangle}
\]

The yield degradation results primarily from a reduction in the hot-spot pressure for low modes and from a reduction in burn volume for mid modes.
The energy distribution in different regions of an implosion is similar for low and mid modes.

Initial distribution at end of acceleration

Final distribution at bang time

\[ \text{TotResE} = IE_{1-D} - IE_h \]

- Radiation loss
- IE: free-fall shell
- IE: shocked shell
- KE: free-fall shell
- KE: shocked shell
- KE: hot spot
- IE: hot spot

Energy (% of \( E_{\text{total}} \))
A general expression is found relating the pressure degradation to the total residual energy and the flow within the hot spot

- Adiabatic compression:
  \[
  \frac{\bar{p}Y_{\Gamma}}{\bar{p}_{1-D}V_{1-D}^\Gamma} = e^{\Delta_{\text{flow}}}
  \]

- Energy conservation:
  \[
  \frac{E_h}{E_{h1-D}} = \frac{\bar{p}Y}{\bar{p}_{1-D}V_{1-D}} + \frac{KE_h}{E_{h1-D}}
  \]

- Hot-spot volume-averaged pressure scaling with total residual energy:
  \[
  \frac{P}{P_{1-D}} = \left(1 - \frac{\text{TotResE}}{E_{h1-D}}\right)^{\Gamma / (\Gamma - 1)} e^{\Delta_{\text{flow}} / (1 - \Gamma)}
  \]
The neutron-averaged observables can differ from the hot-spot volume-averaged quantities; the differences although small for low modes are more pronounced for mid-mode asymmetries.

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*A. Bose et al., Phys. Plasmas 24, 102704 (2017).*