Multidimensional Analysis of Direct-Drive Plastic Shell Implosions on the OMEGA Laser

"Broken" Shell

\[ \rho_{\text{peak}} = 70\% \rho_{\text{peak}}^{(1-D)} \]

Integral Shell

\[ \rho_{\text{peak}} = 100\% \rho_{\text{peak}}^{(1-D)} \]

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2-D simulations of high-adiabat plastic shell implosions on OMEGA are in good agreement with experiment.

- Excellent agreement on laser energy absorption is obtained between experiment and simulation.

- Single-beam nonuniformity significantly influences fusion yields for “thin” (≤ 20 \( \mu \)m thick) shells through shell instability during acceleration, in contrast to the thicker (≥ 27 \( \mu \)m thick) shells.

- Good agreement with experimentally observed neutron production history, areal densities, and x-ray images of self-emission is obtained with 2-D simulations.
Collaborators


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Outline

• Target, pulse shape, and experimental conditions
• Laser drive
• Nonuniformity seeds
• Effect of unstable growth on observables
• Comparison of 2-D simulations with experimental observables
  – neutron production rates
  – areal density
  – ion temperature
  – core x-ray images
• Estimates of turbulent mixing length
A large number of warm plastic shells have been imploded on OMEGA.

A variety of fills provides complementary information\(^*\) on core conditions.

Most implosion observables occur during deceleration, after significant growth during all previous phases of the implosion.

Simulation of 20-\(\mu\)m CH, 15 atm Shell

Growth of single mode \((\ell = 30)\) at fuel–shell interface

Plastic shell implosions provide a stringent test of laser drive modeling, nonuniformity sources, and implosion dynamics.
The laser energy absorption model in hydrodynamic simulations agrees well with measurements.

Absorption Fraction for 1ns-Square Pulse on CH Shells

Absorption fraction

Shot number

*W. Seka, HO1.009
**Nonuniformity Seeds**

Irradiation and target nonuniformities are seeds for unstable growth in ICF implosions.

- Beam mispointing, mistiming, asymmetries in spot shapes, and energy imbalance manifest in low-order (long wavelength) modes.

- Phase plate speckle results in intermediate and short wavelength nonuniformity seeds.

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**Ablation Surface Amplitudes at the Start of the Acceleration Phase**

**Single-beam nonuniformity (laser imprint)**

- **Long wavelengths**
- **Beam imbalances**
- **Surface roughness**

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**Graph Details:**

- **Amplitude (μm)**
- **Mode number**
- **Long wavelengths**
- **Beam imbalances**
- **Surface roughness**
- **Intermediate**
- **Short**
Implosion Dynamics

Two extremes of shell stability are probed on OMEGA by varying the shell thickness.

Multimode simulation of laser imprinting; modes 2–200 at end of acceleration phase.

**“Broken” Shell**
- 20 µm
- \( A_p-v \) (c of m) = 6.6 µm
- 1-D shell thickness = 5 µm

**Integral Shell**
- 27 µm
- \( A_p-v \) (c of m) = 3.4 µm
- 1-D shell thickness = 7 µm
“Broken” shells show a persistence of neutron production due to undercompression.

- Time for shock to transit shell $= \Delta / U_{\text{shock}} \sim \Delta_{\text{perturbed}} > \Delta_{1-D}$
- Disassembly is delayed.
Integral shells result in burn truncation due to unstable fluid flow at the interface.

- Mass flow into the bubbles is an important burn truncation mechanism.
Undercompression is evident in broken shells modeled in two-dimensions using DRACO

Nonuniformity seeds:
Laser imprint \((\ell = 20 \text{ and } 200)\)
Beam-beam imbalances \((\ell = 4)\)

Peak Neutron Production

\[
\rho_{\text{peak}} = 70\% \rho_{\text{peak}} \text{ (1-D)} \quad (20 \, \mu m)
\]

\[
\rho_{\text{peak}} = 100\% \rho_{\text{peak}} \text{ (1-D)} \quad (27 \, \mu m)
\]
Neutron production rates persist in the “thin” shell simulations and truncate in the “thick” shell simulations.

Short wavelengths significantly influence the temporal evolution of the neutron rate for unstable shell, in contrast to the stable shell.
Similar trends in neutron production rates are observed experimentally.
The lower fill pressure for the broken shell does not show a widening of the neutron production rate.
Yields and areal densities from simulation show good agreement with observations.

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*S. P. Regan, CO1.004*  
**Li et al., Phys Plasmas 7, 2578 (2000).**

†J. Frenje, CO1.009
The marginal effect of long and intermediate wavelengths for thin shells is consistent with observations* using new phase plates

- Far field intensity envelope: \( I(r) \propto \exp \left[ -\left( \frac{r}{\delta} \right)^n \right] \)
- New SG4: \( n = 4.1, \delta = 360 \ \mu m \)
- Old SG3: \( n = 2.2, \delta = 308 \ \mu m \)

* S. P. Regan, CO1.004

**Graphs and Images:**

- Calculated on-target \( \sigma_{\text{rms}} \) ratio: SG3/SG4
- Yield relative to 1-D
- Calculations: SG3 irradiation, SG4 irradiation
- On-target ratio: SG3/SG4
- Spherical harmonic \( \ell \) mode
- Yield relative to 1-D for 20 \( \mu m \) and 27 \( \mu m \)
Limb brightening is significantly reduced in 2-D simulations, consistent with observations.

*Post processed with Spect3D, PRISM Computational Sciences, Madison, WI
Amplitude of short wavelengths are consistent with estimates from turbulent mixing

\[ h \sim \alpha \ A_T g t^2 \]

\( \alpha \sim 0.05^* \), \( A_T = 0.18 \), \( gt^2 = 120 \, \mu\text{m} \)

\( h \sim 1 \, \mu\text{m} \) ~ amplitude of short wavelength in simulation

Primary neutron yields are not influenced by the turbulently mixed region

- Secondary neutron rates*, Ar-K shell** spectra, and D³He proton yields* from CD shells are sensitive to small-scale mix.

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