Low-Adiabat, High-Compression Cryogenic Deuterium–Tritium Implosions on OMEGA

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Summary

OMEGA experiments are used to validate theoretical hydrodynamic scaling for $\rho R$, $<T_i>_n$, and yield used in calculating ignition factor.

- The ignition factors (ITF, ITFX, $\chi$) define in-flight shell ($V_{imp}$, $\alpha$) and hot-spot conditions for achieving ignition.
- Current simulations are in agreement with experimental measurements of $<\rho R>_n$, $<T_i>_n$, yield, and bang time.
- Cross-beam transfer is important for understanding experimental results.
- A model has been developed to relate the hot-spot distortion fraction with reduction in $T_i$ and yield.
Collaborators


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Outline

• Ignition design and ignition conditions
• Areal density
  – shock tuning
  – control of short-wavelength perturbation growth
• Hot-spot ion temperature and yield
  – validation of drive efficiency
  – effect of perturbation growth
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The symmetric direct-drive NIF ignition design has a 1-D gain of $\sim 50$

- $E_L = 1$ to $1.5$ MJ
- $V_{imp} = 3.5$ to $4 \times 10^7$ cm/s
- IFAR = 35 to 45
- Gain$_{1-D}$ = 45 to 50
The ignition factors depend on shell conditions and fuel mix

- Ignition threshold factor for the indirect-drive NIF design\textsuperscript{1}

\[
\text{ITF} \sim V^{\text{imp}} \alpha^{-4} \left(1 - 1.2\xi\right)^4 \left(\frac{M_{\text{clean}}}{M_{\text{DT}}}\right)^{0.5}
\]

\[
\alpha = \frac{P}{P_{\text{FERMI}}}
\]

\[
\xi = \text{hot-spot distortion fraction}
\]

\[
M_{\text{DT}} = \text{fuel mass}
\]

ITF = 1 has a 50% probability of achieving ignition.

- Threshold factor\textsuperscript{2}: measured conditions at neutron-production time

\[
\chi = \langle \rho R \rangle^{0.8} \left(\frac{\langle T_i \rangle}{4.7 \text{ keV}}\right)^{1.6} \text{YOC}^{0.5}
\]

\[
\chi > 1 \text{ required for ignition}
\]

- ITFX \sim \chi^3 \text{ (defined in Ref. 3)}

One of the main goals of the cryogenic campaign on OMEGA is to validate modeling of \langle \rho R \rangle, \langle T_i \rangle, and yield.

\textsuperscript{1}S. Haan et al., “Point Design Targets, Specifications, and Requirements for the 2010 Ignition Campaign on the National Ignition Facility,” submitted to Phys. Plasmas
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Areal Density

The shell areal density depends mainly on shell adiabat

\[ \langle \rho \rho' \rangle_n = 1.7 \frac{E_{L,MJ}^{1/3}}{\alpha_{if}^{0.54}} \]

- Shell adiabat is determined by
  - shock heating—optimized in triple-picket design
  - excessive short-scale perturbation growth—controlled by shell IFAR = radius/shell thickness

\[ \rho R_{max} \]

\[ \langle \rho R \rangle_n \]

\[ \rho R \text{ (g/cm}^2) \]

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

Neutron rate (\( \times 10^{24} \text{ s}^{-1} \))

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

Power (TW)

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

\[ ^1 \text{C. Zhou and R. Betti, Phys. Plasmas 14, 072703 (2007).} \]
Areal Density

Shock tuning is performed using VISAR measurements\(^1\)

Velocity Interferometry System for Any Reflector (VISAR)

5 to 10 \(\mu\)m CD + 0.1 \(\mu\)m Al

\(D_2\)

\[^1\text{T. R. Boehly (NO5.00009).}\]
Simulations reproduce shock-velocity data very well for a variety of picket energies and picket timings.
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Accuracy in shock-velocity prediction meets the ignition requirement.
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The areal density is degraded for shells with excessive short-scale perturbation growth.

- Warm CH implosions
- In-flight aspect ratio (IFAR = radius/shell thickness) and adiabat are varied by changing picket energies

\[ \text{Areal Density} \]

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

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

2. P. B. Radha (To5.00003).
The areal density is degraded for shells with excessive short-scale perturbation growth.
The measured areal density in triple-picket cryogenic implosions is larger than 88% of the 1-D predicted value. The areal-density measurements confirm accuracy of shock tuning and shell stability to short-wavelength perturbations.

MRS data
- 55723
- 295±47 mg/cm²

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The measured ion temperature is \(~25\%\) lower than the 1-D predicted value.

Neutron yield and temperature degradation are due to 3-D asymmetry effects or a reduction in hydrodynamic efficiency.
Ion Temperature and Yield: Drive Efficiency

Bang time is an accurate measurement of shell velocity

Neutron-averaged ion temperature*  \( \langle T_i \rangle \sim V_{\text{imp}}^{1.25} \)

\( V_{\text{imp}} = 3.0 \times 10^7 \text{ cm/s} \)  \( \langle T_i \rangle \sim 3.0 \text{ keV} \)

\( V_{\text{imp}} = 2.8 \times 10^7 \text{ cm/s} \)  \( \langle T_i \rangle \sim 2.8 \text{ keV} \)

- Experimental bang time is delayed by \( \sim 80 \text{ ps} \)
- \( \frac{\delta V_{\text{imp}}}{V_{\text{imp}}} = \frac{\delta t_{\text{bang}}}{t_{\text{drive}}} = \frac{80 \text{ ps}}{1300 \text{ ps}} = 6\% \)

The scattered-light measurement indicates a loss in laser coupling.
Beam-to-beam energy transfer leads to a reduction in laser coupling\(^1\)

The transfer of energy from (1) to (2) is due to SBS before deposition\(^2\)

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\(^1\)I. Igumenshchev et al., “Crossed-Beam Energy Transfer in ICF Implosions on OMEGA,” submitted to Phys. Plasmas

When beam-to-beam energy transfer is included, both the bang time and laser absorption are in good agreement with simulations.
Beam-to-beam energy transfer leads to a reduction in the $T_i$ and yield predictions. An additional reduction in $T_i$ and yield is caused by 3-D asymmetry effects.
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Perturbation growth leads to a reduction in “clean” hot-spot volume and ion temperature.

\[ T_i \left( \frac{r}{r_1-D} \right) = \frac{4\pi}{3} r_3-D \leq V_1-D = \frac{4\pi}{3} r_1-D \]

Low-\( \ell \) modes contribute less\(^1\)

\[ r_3-D = r_1-D - \sqrt{\sum_{\ell} (w_\ell a_\ell)^2} = r_1-D (1 - \xi) \]

Extra thermal conduction losses \( \Rightarrow \) lower \( T_e \) and \( T_i \)

\( ^1 \)Kishony, Shvarts, Phys. Plasmas 8, 4925 (2001).
Ion-temperature reduction can be related to the hot-spot distortion fraction.

Ref. 1: \[ PV \sim T^{5/2} \frac{T}{r} \Rightarrow V_a \sim \frac{T^{5/2}}{\rho_{\text{shell}} r} \]

Perturbations move the shell mass closer to center. Ablation is more efficient. There is more mass in the hot spot, along with lower \( T_i \).

\[ \frac{d}{dt} \left( \frac{4\pi}{3} \rho_{\text{hs}} r^3 \right) = 4\pi r^2 \rho_{\text{shell}} V_a \sim rT_{\text{hs}}^{5/2} \]

\[ r_{3-D} = r_{1-D} (1 - \xi), \quad \rho_{\text{hs}} T_{\text{hs}} = \rho_{1-D} T_{1-D} \]

\[ (1 - \xi)^2 \frac{d\rho_{\text{hs}}^{7/2}}{dt} + 21 \frac{\rho_{\text{hs}}^{7/2}}{2} (1 - \xi) \frac{r_{1-D}}{r_{1-D}} = \frac{d\rho_{1-D}^{7/2}}{dt} + 21 \frac{\rho_{1-D}^{7/2}}{2} \frac{r_{1-D}}{r_{1-D}} \]

Ion Temperature and Yield: 3-D

Model prediction for yield and $T_i$ is consistent with the data
2-D simulations confirm temperature reduction predicted by the model
Reducing target offset, ice roughness, and ablator finish is required to improve yield and $T_i$.

Results of 2-D DRACO Simulations

Ion Temperature and Yield: 3-D
Ion Temperature and Yield: 3-D

With nonuniformity sources meeting the goal, \( \alpha = 2 \) cryogenic implosions on OMEGA are predicted to achieve YOC \( \sim 15\% \) to 20\% with \( \langle T_i \rangle_n \sim 2.4 \text{ keV} \).
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Summary/Conclusions

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