Achieving Record Fusion Yields in Direct-Drive Laser-Fusion Experiments Using Statistical Mapping

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OMEGA 30 kJ

NIF 2 MJ

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A reliable predictive capability is required to find the optimum implosion

\[ \rho R \]

**Lawson ignition parameter**

\[ \chi \sim \rho R^{2/3} \text{ yield}^{1/3} \]

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How can we predict the outcome of an implosion experiment? Find correlations to bridge the gap between simulations and experiments.

Laser pulse and target specifications are inputs to both the code and the experiment.

**1-D physics models (LILAC*)**

**Implosion experiment: real physics**

Code output: $\text{Yield}^{\text{LILAC}}, V^{\text{LILAC}}_{\text{imp}}, \rho R^{\text{LILAC}}, T_i^{\text{LILAC}}, \tau^{\text{LILAC}}, R^{\text{LILAC}}$

Measurable parameters: $\text{Yield}^{\text{Exp}}, V^{\text{Exp}}_{\text{imp}}, \rho R^{\text{Exp}}, T_i^{\text{Exp}}, \tau^{\text{Exp}}, R^{\text{Exp}}$

Example: $\text{Yield}^{\text{Exp}} = F(V^{\text{LILAC}}_{\text{imp}}, \rho R^{\text{LILAC}}, T_i^{\text{LILAC}}, \tau^{\text{LILAC}}, ...)$

*1-D hydrodynamic code*
The combination of 1-D simulations and mapping relations provides a predictive capability as long as its validity can be extrapolated.
Systematic changes to the target specifications and laser pulse resulted in the expected increase in yield.

Four shot days (February to July 2017)

- Measured yield
- Prediction from mapping

\[ 4.3 \times 10^{13} \left( \frac{V_{\text{LILAC}}}{400} \right)^{4.2} \left( \frac{M_{\text{LILAC}}}{0.01} \right)^{0.65} \]

- Time shift
- Ramp change
- Foot delay

Thickness \( \Delta_{DT} = 48 \, \mu m \)
Outer diameter (OD) = 870 \( \mu m \)
Sequential shot number

Delta change:
- \( \Delta_{DT} = +3 \, \mu m \)
- \( \Delta_{DT} = +40 \, \mu m \)
- OD = +40 \( \mu m \)
- OD = 910 \( \mu m \)
Designing new implosions using statistical mapping from previous implosions led to tripling the number of fusion reactions on the OMEGA laser.

The equation given is:

\[
\text{YieldExp} \times 10^{14} = (V_{\text{LILAC}}^{\text{imp}})^{4.3} (M_{\text{LILAC}}^{\text{stag}}) (\rho R_{\text{LILAC}}^{\text{LILAC}})^{0.3} \text{OD}_{\text{out}}^{-1.2} \left( \frac{T_{\text{min}}}{T_{\text{max}}} \right)
\]

The graph shows a trend line with data points indicating a mapping relation. The highest yield up to 2016 is 5 x 10^{13}, and the yield for October 2017 is 1.4 x 10^{14}.
A systematic approach is used to find the optimum implosion on OMEGA

- **Velocity campaign**: Larger yield by increasing OD, better coupling, larger $V_{imp}$, larger IFAR

- **Hydro-stability or laser-energy boundary**

- **Optimum implosion**

- **Tuning campaign**: Increase $\rho R$

- **October 3 shots**: as predicted
  \[ Y = 1.4 \times 10^{14}, \rho R = 110 \text{ to } 130 \text{ mg/cm}^2 \]

- **April 4 shots**: as predicted
  \[ Y = 7.8 \times 10^{13}, \rho R = 110 \text{ mg/cm}^2 \]
Hydrodynamic equivalence provides a tool to scale the performance of OMEGA direct-drive implosions to NIF energies.

Scaled hydro-equivalent experiments are carried out on OMEGA.
The latest OMEGA implosions would produce 400 kJ of fusion energy when scaled to the NIF laser drive.
The recent results from OMEGA are exciting and give hope of rapid progress in laser fusion

- By mapping the experimental results onto the simulation database, an accurate predictive capability is developed.
- This new predictive capability was used to design better implosions on the OMEGA laser.
- The highest fusion yield (tripled in the past year) of $1.4 \times 10^{14}$ was achieved by increasing the target outer diameter, reducing the DT ice thickness, and adjusting the laser pulse shape.
The 1-D Campaign developed a database of more-predictable, lower-convergence, high-adiabat implosions.
Higher yields were achieved through CD ablators, thinner ice, 40/60 DT mixture, modified pulse shapes, and larger-diameter shells.

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**Shot 80802**
- \( Y = 3.2 \times 10^{13} \)
- \( \rho R = 126 \text{ mg/cm}^2 \)
- \( T_i = 2.6 \text{ keV} \)

**Shot 87258–69**
- \( Y = 1.2 \text{ to } 1.4 \times 10^{14} \)
- \( \rho R = 100 \text{ to } 130 \text{ mg/cm}^2 \)
- \( T_i = 4.3 \text{ to } 4.6 \text{ keV} \)