Optimization of Direct-Drive Inertial Fusion Implosions Through Predictive Statistical Modeling

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1.9 MJ

Extrapolated fusion energy (kJ)

\( \chi \text{no alpha} \)

- Previous experiments
- Yield campaign
- \( \rho R \) campaign

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Recent results from the yield and optimization campaigns show predictable improvements in performance leading to about 500 kJ of extrapolated yield

- The OMEGA implosion performance can be predicted pre-shot using statistical mapping
- This new predictive capability led to improvements in yields and areal density ($1.6 \times 10^{14}$ with 160 mg/cm$^2$ of average areal density)
- The extrapolated no-alpha ignition parameter $\chi_{\text{no alpha}} = 0.74$ leads to a yield amplification of $3.0 \times$ and extrapolated yield of $\sim 500$ kJ at 1.9 MJ of symmetric illumination
- Further improvements are expected from the optimization campaign and from the upcoming facility upgrades (new phase plates, advanced ablators, fill-tube capability, and possible CBET* mitigation**)

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*CBET: cross-beam energy transfer
**R. Follett, NI2.00005, this conference.
Collaborators


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Optimization of an ICF* target requires a search through an $n > 10$ dimensional space

- Predictive tools are needed to efficiently search through this space
- Relative to the experimental frequency, these tools need to be
  1) accurate when evaluated
  2) quick to evaluate
  3) easily updated with experimental feedback

*ICF: inertial confinement fusion
Simulations have traditionally been the primary predictive tool in ICF, but are not accurate enough to efficiently guide experimental design

- 1-D simulations are computationally inexpensive, and are often used for target design
- These simulations overestimate the yield and areal density, but correctly model the energy coupling and implosion velocity
- 2-D and 3-D simulations are slow, unsuitable for parameter scans, and generally not predictive

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![Graph showing the relationship between measured yield and simulated yield, with a linear regression line.](Graph.png)

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Using the experimental and 1-D simulation database of OMEGA implosions, we construct a function that transforms the code outputs into experimental predictions.

Predictive design process


†FPEOS: first-principle equation of state;
The transformation is derived from statistical mapping relations between experimental observables and 1-D simulation outputs.

Pulse shape + target specs \rightarrow O^{\text{exp}} = F_{\text{exp}}[I_{\text{1-D}}, S_{\text{3-D}}^{\text{sys}}, S_{\text{3-D}}^{\text{ran}}]

Simulated observables \rightarrow O^{\text{sim}}_{1-D} = F_{\text{sim}}[I_{\text{1-D}}, 0, 0] \quad \Rightarrow \quad I_{1-D} = F^{-1}_{\text{sim}}[O^{\text{sim}}_{1-D}]

Constant if systematic
Neglect if experiments are repeatable

O^{\text{exp}} = F_{\text{exp}}[F^{-1}_{\text{sim}}(O^{\text{sim}}_{1-D}), S_{3-D}^{\text{sys}}, S_{3-D}^{\text{ran}}]

O^{\text{exp}} \approx F_{\text{map}}[O^{\text{sim}}_{1-D}] \quad \text{Predict experiment from 1-D simulation}

Existence of mapping relation requires repeatable experiments \rightarrow only systematic nonuniformities.
Power laws are used as basis functions to expand the mapping relation

\[ O_{\text{exp}} \approx F_{\text{map}} \left( O_{1-D}^{\text{sim}} \right) \sim \prod_{i=1}^{N} \left( O_{1-D,i}^{\text{sim}} \right)^{\mu_i} \]

Mapping of simulated $\rho R$

Test on \emph{LILAC} simulations with CBET, nonlocal transport, FPEOS

Mapping of simulated yield

Many choices of variables are suitable for accurate mapping.
Deficiencies in the code physics models can be partially remedied through statistical relations.

Test: recover LILAC with nonlocal + CBET + FPEOS from LILAC flux limiter without CBET

\[ \text{Yield (CBET + FPEOS + NL)} \times 10^{14} \]

\[ \sim \frac{M_{\text{FL}} \langle P_{\text{FL}} \rangle^{2.5} R_0^{6.5} \langle T_{\text{FL}} \rangle^{2.4}}{\rho R_{\text{FL}}^5 V_{\text{FL}}^4} \]

NL: nonlocal thermal transport
FL: flux-limited simulations
Application to OMEGA implosions to increase the fusion yield
The mapping relation correctly predicted a higher yield when the target size was increased.
Larger targets, thinner ice, and changes to the pulse shapes led to higher yields as predicted by the mapping relations.

- The mapping relation evolves as more shots are added.

\[
Yield_{\text{pred}} = 4.2 \times 10^{13} \left( \frac{V_{\text{imp}}}{400} \right)^{4.2} \left( \frac{M_{\text{stag}}}{0.01} \right)^{0.6}
\]

\[
Yield_{\text{pred}} = \frac{4.4 \times 10^{13}}{R_{T}^{0.6}} \left( \frac{V_{\text{imp}}}{400} \right)^{4} \left( \frac{M_{\text{stag}}}{0.01} \right)^{0.6} \left( \frac{\rho R_{\text{stag}}}{110} \right)^{0.3} \left( \frac{415}{R_{0}} \right)^{0.6}
\]
“Random” effects lead to ~10% yield variation and are accounted for post-shot through the measured ion temperature asymmetries

- Random variations in yield are caused by target offsets, power imbalance, and surface roughness
- nTOF* detectors measure the ion temperature along six lines of sight
- The ion temperature asymmetry metric, $R_T = \frac{T_{\text{max}}}{T_{\text{min}}}$, acts as a proxy for this effect
- The yield is degraded by $\approx R_T^{-0.6}$

* nTOF: neutron time-of-flight
Tripling of the fusion yield was achieved in seven shot days using statistical mapping predictions.
Application to OMEGA implosions to increase the areal density at high yields
The areal density was increased by ~65%, keeping the yield above $10^{14}$ using the model predictions.
The increase in areal density was obtained through adjustments to the pulse shape and target specifications.
The best performing implosions used a new pulse shape and exhibited both high yields and areal density.

Yield: $1.4 \times 10^{14}$, $1.56 \times 10^{14}$

Radius ($\rho R$): 100, 160

Radius (GMXI-c, $\mu$m): 33, 28

GMXI: gated monochromatic x-ray imager

D. Patel et al., GO6.00006, this conference.
Performance degradation mechanisms for OMEGA implosions
The in-flight-aspect-ratio (IFAR) appears as a key figure of merit in the statistical predictions of both yield and $\rho R$

- Mixing front from imprint travels distance $h \sim \beta gt^2 \sim \beta R_0$, and fraction of shell comprised
  
  $$\frac{h}{\Delta} \sim \frac{\beta R_0}{\Delta} = \beta \text{IFAR}$$

- $\beta \sim 0.03$ to 0.07

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**Statistical models**

- $Y_{\text{exp}} \sim \frac{1}{\text{IFAR}^{1.2}}$
- $\rho R_{\text{exp}} \sim \frac{1}{\text{IFAR}^{0.5}}$
Three-dimensional *ASTER* simulations indicate that high modes from laser imprinting ($\ell > 100$) are limiting the performance at high IFAR’s.

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SSD* on/off experiments show that laser imprinting causes 30% degradation of areal density at higher IFAR’s.

High-performance implosions are degraded by imprint.

* SSD: smoothing by spectral dispersion
The role of high modes will be clarified through mitigation techniques that are under development

- New ablator designs, such as the recently tested polystyrene ablators, show lower levels of surface imperfections than the CD ablators currently in use*
- Foam-coated ablators have the potential to reduce the effects of laser imprint**
- Future experiments will investigate whether increasing the SSD bandwidth can further mitigate laser imprint
- Fill-tube–based target fills can create a more-uniform ice layer and reduce the amount of tritium damage to the targets†
- New, smaller DPP’s‡ (R75‡‡) may enable high-velocity implosions at lower IFAR’s

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†D. R. Harding et al., Fusion Sci. Technol. 73, 324 (2018).
‡DPP: distributed phase plates
Hydrodynamic scaling of OMEGA implosions to NIF energies
The performance metric is the generalized Lawson criterion scaled to NIF energies

- Initially assumes symmetric illumination
- Polar-drive extrapolation will follow

Scale 1:70 in energy

OMEGA 26 kJ

0.86 mm

Direct drive NIF 1.9 MJ

3.6 mm

Hydrodynamic scaling

Hydro scaling provides a simple and robust tool to scale OMEGA performance to NIF energies

<table>
<thead>
<tr>
<th>Same hydro for OMEGA and NIF</th>
<th>LPI* not included in hydro scaling</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Same implosion velocity and adiabat</td>
<td>• Hydro scaling does not account for differences in LPI</td>
</tr>
<tr>
<td>• Same final hot-spot pressure and shell density</td>
<td>• LPI depends on size and is different for OMEGA and the NIF</td>
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<tr>
<td>• Mass and volume scale with laser energy</td>
<td>• Assessing the impact of LPI on the NIF requires dedicated experiments on the NIF (DD MJ campaign on NIF)</td>
</tr>
<tr>
<td>• Same energy coupling to target</td>
<td>• Results from planar and sub-scale spherical experiments on NIF suggest that hot electron levels will be manageable in direct-drive ignition designs</td>
</tr>
<tr>
<td>• All nonuniformities scale with size (conservative for NIF since ice roughness/target –radius is less and impact of fill tube is less)</td>
<td></td>
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</tbody>
</table>

OMEGA will validate the hydrodynamics (that scales), while the NIF will assess the LPI (that does not scale).

*LPI: laser–plasma interaction
M. Rosenberg et al., CO4.00005, this conference.
A. A. Solodov et al., JO6.00010, this conference.
The no-alpha hydro scaling can be explained with simple physics

- No-alpha scaling, pure hydrodynamics, and thermal transport

Same NIF and OMEGA

Higher on NIF by \( \sim 40\% \) because larger volume/surface ratio \( \sim E_L^{0.1} \)

Scale as \( E_L \)

Scale as \( E_L^{1/3} \)

\[
\gamma \sim P^2 \left( \frac{\sigma v}{T^2} \right) V_T
\]

\[
\gamma_{\text{NIF no } \alpha} \approx \left( \frac{E_{\text{NIF}}}{E_{\text{OMEGA}}} \right)^{1.43} \times \gamma_{\text{OMEGA no } \alpha}
\]

\[
\gamma_{\text{NIF no } \alpha} \approx 400 \times \gamma_{\text{OMEGA no } \alpha}
\]

- at 1.9 MJ

\[
1.6 \times 10^{14} \rightarrow 6 \times 10^{16}
\]

\[
\gamma_{\text{NIF no } \alpha} \approx 540 \times \gamma_{\text{OMEGA no } \alpha}
\]

- at 2.5 MJ

\[
1.6 \times 10^{14} \rightarrow 8.7 \times 10^{16}
\]

The effect of alpha heating is assessed through simple theory or simulations of hydro-equivalent targets.

Hydroscaled simulations

![Graph showing densities at peak neutron rate with and without alpha heating.]

Analytic model

\[ \chi_{no \alpha} = \rho R_g^{0.61} \left( \frac{0.12 Y_{16}}{M_{stag}} \right)^{0.34} \left( \frac{E_{NIF}}{E_{OMEGA}} \right)^{0.34} \]

\[ \dot{Y}_{\alpha}^{amp} \approx \left(1 - \chi_{no \alpha}^{NIF} \right)^{-3/4} \]

The highest-yield OMEGA implosions from the Optimization Campaign scale to 500 kJ of fusion energy at 1.9 MJ of symmetric drive (to 1 MJ for a 2.5-MJ drive)

![Graph of extrapolated fusion energy vs. \( \chi_{\text{no alpha}} \) for 1.9 MJ and 2.5 MJ drives.](attachment:image.png)
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Because of higher temperatures, recent implosions require lower pressures and lower convergence to achieve hydro-equivalent ignition conditions.

$P_{\text{nucl}} = \text{pressure from nuclear measurement}$

$P_{\text{x ray}} = \text{pressure from x ray measurement}$

Ignition is defined as 1 MJ of fusion yield.

The x-ray pressure uses one reference nuclear measurement for absolute value.

*OC: optimization campaign
Interpreting the mapping relations provides physical insight in the target design

Mapping relation (less accurate) for average measured areal density

\[
\rho R_{n\text{TOF} + \text{MRS}} \sim \left( \frac{\rho}{T} \right)_n^{0.7} \frac{1}{F_{\text{coast}}^2} \frac{1}{F_{\text{laser}}^5} \left( \frac{R_{out}}{R_{in}} \right)^4 R_{out}
\]

\( \langle \rho \rangle_n \rightarrow \) High simulated convergence is good

\( \langle T \rangle_n \rightarrow \) Will pay a price by increasing \( T_i \) but mitigated if one uses higher \( R_{out} \)

\( \left( \frac{R_{out}}{R_{in}} \right) \rightarrow \) Thicker ice helps

\( F_{\text{coast}} \sim 1 + t_{\text{coast}} / t_{\text{imp}} \rightarrow \) No coasters give higher \( \rho R \)

\( F_{\text{laser}} \sim 1 + t_{\text{laser}} / t_{\text{imp}} \rightarrow \) Get high \( \rho R \) with shortest possible laser pulses
Including lower-adiabat implosions shows the yield increase from convergence is less than 1-D predictions while the areal density scales as 1-D.

In experiments, a higher convergence ratio (CR) leads to a very modest increase in yield.

\[ \rho R (\text{MRS}^*) \] (mg/cm²)

Neutron yield: experiment versus LILAC param + CR_{Exp}

1-D theory

\[ 100 \left( \frac{\text{CR}_{\text{Exp}}}{13} \right)^{1.7} \]

1-D theory

\[ 4 \times 10^{13} \left( \frac{V_{\text{LILAC}}}{400} \right)^4 \left( \frac{M_{\text{stag}}}{0.01} \right)^{0.7} \left( \frac{\text{CR}_{\text{Exp}}}{11} \right)^{0.5} \]
The hydro-scaled laser pulses do not exceed 500 TW.
The sensitivity of the areal density to the details of the laser pulse shape (i.e., shock timing) and the large measurement errors ($\approx \pm 10\%$) complicate the predictions.

- Mapping of the full $\rho R$ database provides a less accurate but more general prediction.
- Using a subset of $\rho R$ data improves accuracy by limiting the parameter space of laser pulse shapes and target specs.