Understanding the Fusion Yield and All of Its Dependencies Using Statistical Modeling of Experimental Data

Aarne Lees
University of Rochester
Laboratory for Laser Energetics

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Degradation mechanisms and their dependencies are uncovered by the statistical mapping model for OMEGA direct drive implosions

- A physics-based mapping model of the measured fusion yield onto the 1-D simulation database of OMEGA direct-drive implosions reveals dominant and subdominant degradation mechanisms.

- The yield degradation with respect to 1-D simulations is quantified and it results from:
  - hydrodynamic effects (stability and/or model deficiencies)
  - laser beam to target size ratio (underfilling the target)
  - age of the DT fill and He$^3$ contamination*
  - $\ell = 1$ mode from mispointing and target offset**

- Using the mapping model, the measured yield of an implosion can be corrected for each degradation mechanism, thereby enabling proper comparison between implosions and guiding target design changes.
Collaborators


Laboratory for Laser Energetics, University of Rochester

M. Gatu Johnson, R. D. Petrasso, C. K. Li, and J. A. Frenje

Plasma Science and Fusion Center, Massachusetts Institute of Technology
Outline

- A physics-based statistical mapping model
- Degradation from the fill age and He$^3$ accumulation
- Degradation from the $\ell = 1$ mode
- Degradation from $R_b/R_t$
- Degradation from hydrodynamics: instabilities and/or inaccuracy in physics models
- Predictions of highest yields on OMEGA
A physics-based statistical mapping model
Multiple systematic and random mechanisms degrade the performance of OMEGA implosions

Random degradations

Systematic degradations

Offset + mispointing

Age ~ 14 days

He build up $\beta$-decay damage

Laser absorption pattern

Isolated defects

Rayleigh-Taylor growth

nTOF: neutron time of flight

CBET: cross-beam energy transfer
If experiments are systematically perturbed, it is possible to construct a predictive model from 1-D hydrocodes and relevant input parameters.

**Generalization of mapping model by Gopalaswamy et al.**

\[ Y^{\text{exp}} = F \left[ O^{1D}_{\text{sim}}, I_{\text{other}}, S^{\text{sys}}_{3D}, R^{\text{ran}}_{3D} \right] \]

- **Output of 1-D codes**
- **Inputs not accounted for in simulations** (e.g., fill age)
- **Systematic nonuniformity seeds** (e.g., finite laser beam size)
- **Random nonuniformity seeds** (e.g., target offset)

\[ Y^{\text{exp}} = F_1 \left[ O^{1D}_{\text{sim}}, S^{\text{const}}_{3D} \right] F_2 \left[ I_{\text{other}} \right] F_3 \left[ R_{3D} \right] F_4 \left[ S^{\text{var}}_{3D} \right] \]

- **\( S^{\text{const}}_{3D} \)** Constant systematic seeds (uncertain)
- **\( S^{\text{var}}_{3D} \)** Variable systematic seeds (e.g., beam size)

Assume effects of \( I_{\text{other}}, R_{3-D}, \) and variable-\( S_{3-D} \) are subdominant and can be decoupled.

\[ * V. Gopalaswamy et al., Nature 565, 581 (2019). \]
A physics-based model to understand the fusion yield is obtained through the product of different effects

Dividing by the simulated 1-D yield leads to the yield-over-clean (YOC)

\[ \text{YOC}_{\text{exp}} \equiv \frac{Y_{\text{exp}}}{Y_{1\text{D}}^{\text{sim}}} \]

\[ Y_{\text{exp}} = F_1 \left[ O_{1\text{D}}^{\text{sim}} \right] F_2 \left[ I_{\text{other}} \right] F_3 \left[ R_{3\text{D}} \right] F_4 \left[ S_{3\text{D}}^{\text{var}} \right] \]

- Hydrodynamic instabilities + 1-D physics deficiencies
- DT fill age + He\(^3\) accumulation
- Offset + mispointing
- Finite beam size

Residual dependence (see Betti et al. at this conference)*

\[ \text{YOC}_{\text{exp}} \approx \text{YOC}_{\text{hydro}} \left[ O_{1\text{-D}}^{\text{sim}} \right] \text{YOC}_{\text{fuel}} \text{YOC}_{\ell=1} \text{YOC}_{\text{beam}} \text{YOC}_{\text{res}} \]

Output of 1-D simulations

* R. Betti et al., BO09.00011, this conference.
Each YOC is approximated by power law dependencies of relevant variables.

For example:

\[ \text{YOC}_{\text{beam}} \sim \left( \frac{R_b}{R_t} \right)^\gamma \]

Nonlinear global fit (mapping) of YOC\textsuperscript{exp} to all variables produces exponents and confidence levels.

Each individual dependence can be visualized by isolating it from all others.

\[ \text{YOC}_{j}^{\text{exp}} \equiv \frac{\text{YOC}_{\text{exp}}}{\prod_{i \neq j} \text{YOC}_i} \rightarrow \text{YOC}_j \]
Generalizing model predictions to new designs requires a training set with a large variety of physical conditions.

- Fill age ranging from 3 to 97 days
- $T_{\text{max}}/T_{\text{min}}$ reaching as high as 1.7
- $R_b/R_t$ ranging from 0.69 to 1.05
Degradation from tritium radiation damage and He$^3$ accumulation
He$^3$ accumulation and $\beta$-radiation damage of ablator* are possible degradation mechanisms; fuel composition can be chosen to optimize performance.

- In general:  $\text{YOC}_{\text{fuel}} = F[\theta_T, \theta_D, t_{\text{age}}]$
  - $\theta_T$ = ice tritium fraction
  - $\theta_D$ = ice deuterium fraction
  - $t_{\text{age}}$ = time between end of diffusion fill and shot time

- Instead of the fill age, we use the 1–D simulated degradation from He$^3$ contamination assuming 100% accumulation in the vapor

$$\xi_{\text{He}^3} \equiv \frac{Y_{1D}^{\text{sim}}(\text{DT} + \text{He}^3)}{Y_{1D}^{\text{sim}}(\text{DT})}$$

Maximizing $\text{YOC}_{\text{fuel}}$ provides the optimum fuel composition for a given fill age

- **General form**

  $$\text{YOC}_{\text{fuel}} = F[\theta_T, \theta_D, \xi_{\text{He}}^3]$$

- **Monotonic power law dependences are assumed**

  $$\text{YOC}_{\text{fuel}} = \theta_T^\delta \theta_D^\nu \xi_{\text{He}}^\phi$$

  $$\theta_D = 1 - \theta_T$$

- If $\nu \delta > 0$ and $\xi_{\text{He}} = 1$ (shot right after fill), optimum fuel composition occurs for

  $$\max[\theta_T^\delta (1 - \theta_T)^\nu]$$
The fill-age degradation is slightly faster than 1-D code predictions from 100% He³ accumulation in the vapor region; optimum fuel composition occurs at 60% tritium fraction.

- Mapping to data:

\[ \text{YOC}_{\text{fuel}} = \theta_T^{2.2} \theta_D^{1.4} \xi_{\text{He}^3}^{1.2} \]

\[ \xi_{\text{He}^3} = \frac{Y_{1D}^{\text{sim}}(\text{DT + He}^3)}{Y_{1D}^{\text{sim}}(\text{DT})} \]

Optimum fuel composition occurs at 60% tritium fraction.
Degradation from offset and mispointing
The effects of the $\ell = 1$ mode from offset and mispointing are assessed for each shot through the measured $T_i$ asymmetries.

- In 3-D simulations, the yield degradation from the $\ell = 1$ mode is a monotonic function of $T_{\text{max}}/T_{\text{min}}$.

The yield degradation from the $\ell = 1$ mode extracted from the implosion database is in good quantitative agreement with the results of 3-D simulations.

- The minimum relevant detectable $T_i$ asymmetry is determined by the $T_i$ measurement error $\sim 300$ eV ($\sim 10\%$).

- Power law approximation

\[
\text{YOC}_{\ell=1} \approx \min \left[ 1, \left( \frac{T_R^{\text{min}}}{T_R} \right)^{\mu} \right] \quad \text{where} \quad \frac{T_R}{T_{\text{max}}} = \frac{T_{\text{min}}}{T_{\text{max}}}
\]

- Mapping to data:

$$\mu = 1.55 \text{ and } T_R^{\text{min}} \approx 1.14$$

- Note the good agreement with 3-D simulations ($\mu_{\text{sim}} = 1.53$) and $T_R^{\text{min}}$ consistent with measurement error ($\sim 10\%$).

*O. Mannion, K102.00001, this conference (invited).
Degradation from finite laser beam size
Degradation from finite laser beam size is significant for the larger-sized targets used to improve energy coupling and reduce CBET

- Using larger-diameter targets to improve coupling leads to port geometry illumination nonuniformities
- This degradation depends on ratio of beam to target radius $R_b/R_t$
- Using 3-D ASTER* simulations, three regimes are identified:
  I. Yield is not degraded by finite $R_b/R_t$
     $$\text{YOC}_{\text{beam}} \approx 1$$
  II. Yield is degraded as a power law
     $$\text{YOC}_{\text{beam}} \approx (R_b/R_t)^{2.2}$$
  III. Yield degrades faster than power law when the shell is broken up

Degradation from finite laser beam size is significant for the larger-sized targets used to improve energy coupling and reduce CBET.

** V. Gopalaswamy et al., GO10.00002, this conference.
Mapping to the data shows that yield degradation from finite beam size in OMEGA implosions is in the power law regime

- Mapping to data yields stronger dependence than 3-D simulations
  \[ \text{YOC}_{\text{beam}} \approx \left(\frac{R_b}{R_t}\right)^{3.4} \]
- Large yield degradation comes from finite beam size in the best-performing implosion (shot 96806 with \( R_b/R_t = 0.86 \))
  \[ \text{YOC}_{\text{beam}}^{96806} \approx 0.61 \]
- Note that 3-D simulations do not predict significant degradation in shot 96806 from \( R_b/R_t \)
- Other degradation mechanisms or inaccuracies in the 1-D simulations cannot be excluded.

Dedicated experiments with varying \( R_b/R_t \) are planned in November*

\* C. A. Thomas et al., BO09.00010, this conference.
Degradation from systematic hydrodynamic instabilities and 1-D physics model deficiencies
Hydrodynamic instabilities, shock mistiming, and decompression during coasting are all possible degradation mechanisms

- Overall degradation from instabilities and other hydro effects
  \[ \text{YOC}_{\text{hydro}} = \text{YOC}_H[\alpha_{1D}^{\text{sim}}, \text{IFAR}_{1D}^{\text{sim}}, \text{CR}_{1D}^{\text{sim}}, t_{\text{coast}}^{\text{sim}}, t_{\text{shock}}^{\text{sim}}] \]

- Adiabat \( \alpha \) \text{\Rightarrow stability of short and mid modes}
- In-flight aspect ratio (IFAR) \text{\Rightarrow stability of short wavelength modes}
- Convergence ratio \text{\Rightarrow stability of all modes (related to \( \alpha \))}
- Coasting time \text{\Rightarrow decompression and deceleration phase instabilities}
- Shock breakout time \( t_{\text{sb}} \) \text{\Rightarrow depends on adiabat and therefore related to both shock mistiming and stability}
Best fit to the data occurs when variables are combined and reduced to only three independent parameters

- Reduction of hydrodynamic degradation to three independent parameters

\[ YOC_{\text{Hydro}} \sim \alpha e^{T_c \phi} \]

**Adiabat**

Dimensionless coasting time

**Relative shock breakout time**

\[ T_{\text{rel}} = \frac{R_0/V_{\text{imp}}}{t_{\text{sb}}(A_0/16) + (t_{\text{imp}}^{\text{max}} - t_{\text{sb}})} \sim \text{IFAR}^{-0.2} \text{CR}^{-0.25} \]

**Shock breakout time**

**Time of peak implosion velocity**

**Initial aspect ratio**

**Dimensionless coasting time**

\[ T_c \sim \frac{t_{\text{imp}}^{\text{max}}}{t_{\text{bang}}} \]
Mapping to the data reveals a trend of strong yield degradation at low adiabats, high IFAR and high CR

- Mapping to data: \( YOC_{\text{hydro}} \approx \alpha^{0.8} T_{\text{rel}}^{2.6} T_c \)
- YOC is maximized at
  a) high adiabats
  b) shortest shock breakout time versus implosion time
  c) minimum coasting
- Best performing 96806 is degraded by hydro effects

\( YOC_{96806}^{\text{hydro}} \approx 0.65 \)
The measured yield of past experiments can be corrected for fill age and $\ell = 1$ degradation for valid comparison to identify true highest-yield shot

- Given low $\ell = 1$ asymmetry and short fill times, several shots would have exceeded the yield of the record shot 96806

- The corrected record yield shot is a 1010-\(\mu\)m-OD target recently designed based on this analysis (previous record shot was a 960-\(\mu\)m-OD)

These corrections are used to guide future design choices. Increasing the yield of OMEGA best performer to \(2\times10^{14}\) (at fixed $\rho R=160\text{mg/cm}^2$) hydroscales to \(~0.8\text{MJ}\) of fusion yield at 2MJ of symmetric illumination
Summary/Conclusions

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- Using the mapping model, the measured yield of an implosion can be corrected for each degradation mechanism, thereby enabling proper comparison between implosions and guiding target design changes.

Current highest-yield implosions with optimum target size, good laser pointing, and short DT fills are predicted to achieve a neutron yield of \( \approx 2 \times 10^{14} \)***.

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** O. Mannion, K102.00001, this conference (invited).

*** R. Betti et al., BO09.00011, this conference.