Experimentally Inferred Fusion Yield Dependencies of OMEGA Inertial Confinement Fusion Implosions

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Statistical modeling of experimental and simulation databases has enabled the development of an accurate predictive capability for deuterium-tritium layered cryogenic implosions at the OMEGA laser [V. Gopalaswamy et al.,Nature **565**, 581 (2019)]. In this letter, a physics-based statistical mapping framework is described and used to uncover the dependencies of the fusion yield. This model is used to identify and quantify the degradation mechanisms of the fusion yield in direct-drive implosions on OMEGA. The yield is found to be reduced by the ratio of laser beam to target radius, the asymmetry in inferred ion temperatures from the $\ell = 1$ mode, the time span over which tritium fuel has decayed, and parameters related to the implosion hydrodynamic stability. When adjusted for tritium decay and $\ell = 1$ mode, the highest yield in OMEGA cryogenic implosions is predicted to exceed 2×10^{14} fusion reactions.

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In laser-driven inertial confinement fusion (ICF) [1], focused laser light (direct drive [2]) or x rays from a laser-heated hohlraum (indirect drive [3]) are used to implode a spherical shell layered with solid deuterium-tritium fuel (DT ice). The implosion is designed to attain the conditions required to initiate nuclear fusion reactions in the central compressed core (the hot spot) upon convergence and stagnation of the imploding shell. The fusion yield or number of fusion reactions, which is measured through detection of the 14 MeV neutrons produced in the $D + T$ fusion reactions, is one of the key metrics determining the fusion performance of an ICF implosion. It is therefore crucial to determine all the dependencies of the fusion yield so they can be controlled and the fusion yield increased.

In terms of pure hydrodynamics (pressure, temperature, density, and confinement time) and using the so-called no-alpha metrics [4,5], the Lawson triple product in current indirect-drive National Ignition Facility (NIF) [6] implosions is about 70% of the value required for ignition [7]. Direct-drive OMEGA [8] implosions have also achieved similar values of the Lawson parameter when hydrodynamically scaled to NIF laser energies [9]. This suggests that only modest improvements in core conditions are required to exceed the ignition threshold. Therefore it is critical to identify all the possible avenues to improve performance, even those of marginal impact. For instance, as shown in Ref. [9], a 30% increase in yield (to 2×10^{14}) at constant areal density and DT mass in OMEGA best-performing implosions would be sufficient to achieve conditions that hydrodynamically scale to a megajoule of fusion yield at 2 MJ of laser energy for symmetric illumination while a 40% increase in both yield and areal density would scale to ignition.

ICF implosions are complex nonlinear processes that are highly sensitive to many input parameters. The lack of an accurate simulation capability, the low shot rate of laser implosion facilities, and the effects of shot-to-shot variations make it difficult to extract single parameter dependencies, thereby preventing guided improvements in implosion performance. In this Letter, the different dependencies of the fusion yield are extracted from the OMEGA experimental database, and the highest fusion yield achievable on OMEGA is estimated. The major degradation mechanisms are parametrized by the ratio of the laser spot size (R_b) to the target size (R_t), which is not predicted by current radiation-hydrodynamic codes; the age of the DT fuel fill (a proxy of ^{3}He contamination [10] and tritium-radiation damage [11–13]); the mode $\ell = 1$ from offset and mispointing; and 1D parameters accounting for the effects of hydrodynamic instabilities. All such dependencies are quantitatively determined over a database of 177 implosions. The importance of these results is twofold. First they identify the degradation mechanisms, and second they enable one to predict how the yield improves if each degradation is mitigated. When applied to OMEGA implosions, the results indicate that the highest yield achievable on OMEGA should exceed 2×10^{14} neutrons with only minor adjustment to the laser pointing and by reducing the fill age. Yields close to 3×10^{14} are predicted if the degradation from R_b/R_t is mitigated.

In Ref. [9], a statistical model was applied to the fusion yield and used as a "black box" predictive model, which led to impressive increases in the yield without providing insights into the underlying physics. The main novelty of this Letter is the physics-based nature of the new model presented here, showing that it can uncover the physics governing the fusion yield in addition to providing accurate predictions. The analysis uses a similar framework to Ref. [9] to isolate the effects of single parameters on the measured neutron yield. It accurately accounts for dominant dependencies so that subdominant ones can also be identified. The OMEGA database spans a large region of implosion design space with neutron yields varying from 1.0×10^{13} to 1.6×10^{14}. Such large variation in implosion dynamics requires carefully accounting for all major factors that influence the outcome of experiments in order to infer any trends in the data. A χ^2 minimization of the global mapping of simulation outputs onto measured neutron yields is used in this Letter to extract the yield dependencies. More complex statistical analyses can be performed using neural networks ([14,15]).

As argued in Ref. [9], the contribution to fusion yield from the true 1D dynamics and any systematic nonuniformity can be described by a function of simulated 1D parameters. This is true even if the 1D simulations are inaccurate and/or the physics models are incomplete as long as the relation between the input parameters to the codes (laser pulse shapes and target specifications) and the code output parameters is single valued. The effects of nonsystematic (random) nonuniformities can be accounted for but require a shot-specific experimental signature to quantify the impact. When repeated, OMEGA implosions exhibit modest shot-to-shot variations due to randomlike events such as vibrations of the target mount (target offset) and laser mispointing. The consequent yield variations are accompanied by variations in the apparent ion temperature (T_i) that is measured by neutron time-of-flight (NTOF) detectors along six lines of sight [16]. The spherical harmonic induced by target offset or mispointing is an $\ell = 1$ mode with the characteristic flow structure of a jet that widens the NTOF signal used to infer the ion temperature according to the Brysk formula [17–20]. If measured in 4π, the apparent T_i from an $\ell = 1$ mode exhibits a minimum and a maximum value, with the minimum value being close to the true thermal temperature of the hot spot. Therefore, the magnitude of the $\ell = 1$ mode can be related to the so-called asymmetries in the apparent ion temperatures, leading to a dependency of the yield on the T_i asymmetries. Aside from these random events, the outcome of OMEGA implosions is determined by systematic factors. These can be divided into the following categories: (i) 1D dynamics, determined by the laser pulse shape and the target specifications; (ii) systematic nonuniformities in target or laser illumination (e.g., the OMEGA beam geometry, laser speckle pattern, the stalk holding the target, and target roughness); and (iii) systematic changes such as different phase plates [21] or differences in the filling and layering of the targets. Since no signatures of random events beyond the $\ell = 1$ and its T_i asymmetries are observed, all other nonuniformities in OMEGA implosions are systematic and therefore initiated by approximately constant seeds.

Generalizing the conclusions of Ref [9], the measured fusion yield $\mathbf{Y}^{\mathrm{exp}}$ is written as

$$\mathbf{Y}^{\mathrm{exp}} = \mathbf{F}_{\mathrm{map}}[\mathbf{O}_{\mathrm{1D}}^{\mathrm{sim}}, \mathbf{S}_{\mathrm{3D}}^{\mathrm{const}}, \mathbf{S}_{\mathrm{3D}}^{\mathrm{var}}, \mathbf{S}_{\mathrm{3D}}^{\mathrm{ran}}, \mathbf{I}_{\mathrm{other}}^{\mathrm{sys}}], \tag{1}$$

where $\mathbf{F}_{\mathrm{map}}$ is a functional relation, $\mathbf{O}_{\mathrm{1D}}^{\mathrm{sim}}$ are output variables of 1D codes, $\mathbf{S}_{\mathrm{3D}}^{\mathrm{const}}$ and $\mathbf{S}_{\mathrm{3D}}^{\mathrm{var}}$ are both systematic nonuniformity seeds with the former being constant for all shots in the database while the latter can vary (e.g., laser spot size), $\mathbf{S}_{\mathrm{3D}}^{\mathrm{ran}}$ are random nonuniformity seeds, and $\mathbf{I}_{\mathrm{other}}^{\mathrm{sys}}$ are systematic inputs present in experiments but not correctly captured by 1D simulations. Examples of $\mathbf{I}_{\mathrm{other}}^{\mathrm{sys}}$ are ^{3}He contamination and damage to the ablator from tritium beta decay dependent on the fill age and fuel composition. The yield is assumed to be dominated by the implosion velocity, which is typically well simulated by the 1D code LILAC [22] as indicated by shell trajectory measurements [23]; and therefore, the yield is expected to depend on the simulated 1D yield $\mathbf{Y}_{\mathrm{1D}}^{\mathrm{sim}}$. All degradations are denoted as **YOC** or yield over clean. The degradation due to hydrodynamic instabilities from systematic nonuniformities is denoted as $\mathbf{YOC}_h$. Since the systematic nonuniformity seeds are just constants, the resulting degradation is only a function of simulated 1D parameters $\mathbf{YOC}_h[\mathbf{O}_{\mathrm{1D}}^{\mathrm{sim}}]$ [9]. All other dependencies are assumed to be subdominant and therefore approximately decoupled from the others, leading to the following intuitive formulation of the fusion yield:

$$\mathbf{Y}^{\mathrm{exp}} = \mathbf{YOC}^{\mathrm{exp}}\mathbf{Y}_{\mathrm{1D}}^{\mathrm{sim}}$$
$$\mathbf{YOC}^{\mathrm{exp}} \approx \mathbf{YOC}_h\mathbf{YOC}_f\mathbf{YOC}_b\mathbf{YOC}_{\ell=1}\mathbf{YOC}_{\mathrm{res}}, \tag{2}$$

where $\mathbf{YOC}_f$ is the degradation due to DT fill age, tritium damage, and ^{3}He accumulation; $\mathbf{YOC}_b$ is the degradation from a finite laser beam size; and $\mathbf{YOC}_{\ell=1}$ is the degradation from the $\ell = 1$ mode. $\mathbf{YOC}_{\mathrm{res}}$ denotes a weak ($\leq 15\%$ over the entire database) residual size scaling not captured by 1D hydrocodes [24,25] and is approximately constant for high performance OMEGA implosions. Each **YOC** term is analyzed and extracted by mapping onto the experimental database. See the Supplemental Material [26], which includes Refs. [27–30], for additional details of the physics of each degradation term.

We start with the degradation from target offset and laser mispointing leading to $\ell = 1$ perturbations $\mathrm{YOC}_{\ell=1}$. As shown in Ref. [31] using 3D simulations, the yield degradation from $\ell = 1$ can be approximated as a power law of the temperature ratio between the maximum and minimum apparent ion temperature $R_T = T_i^{\max}/T_i^{\min}$ leading to $\mathrm{YOC}_{\ell=1} \sim R_T^{\mu}$ with $\mu \simeq -1.5$. Since the T_i measurement error is about 10%, only implosions with R_T greater than a minimum threshold $R_T^{\min} \approx 1.1$ are expected to exhibit detectable degradation. Therefore, the degradation from the $\ell = 1$ mode is approximated as

$$\mathrm{YOC}_{\ell=1} \sim \hat{R}_T^{\mu}, \qquad \hat{R}_T \equiv \mathrm{Max}\left[1, \frac{R_T}{R_T^{\min}}\right]. \qquad (3)$$

Here the values of μ and $R_T^{\min}$ are obtained through the global mapping onto the data.

The degradation from the DT fill age, ^{3}He accumulation, and β-radiation damage, as well as any isotopic effects YOC_f depends on the time between the DT fill and the shot time (fill age), and the tritium and deuterium concentrations (θ_{T} and θ_{D}, respectively). Instead of the fill age, one can use the 1D simulated yield degradation $\xi_{\mathrm{He}} = Y_{\mathrm{1D,He}}^{\mathrm{sim}}/Y_{\mathrm{1D}}^{\mathrm{sim}}$, where $\mathrm{Y}_{\mathrm{1D,He}}^{\mathrm{sim}}$ includes the ^{3}He produced over the course of the fill age, all of which is assumed to be accumulated in the vapor region. Power law dependencies are assumed leading to

$$\mathrm{YOC}_f \sim \theta_{\mathrm{T}}^{\delta} \theta_{\mathrm{D}}^{\nu} \xi_{\mathrm{He}}^{\phi}. \qquad (4)$$

Note that maximizing the power law combination of $\theta_{\mathrm{T}}^{\delta}$ and $\theta_{\mathrm{D}}^{\nu} \equiv (1-\theta_{\mathrm{T}})^{\nu}$ enables one to find the optimum fuel composition in the case $\delta\nu > 0$. If the implosions exactly follow the 1D code predictions, then $\delta = 0$, $\nu = 0$, and $\phi = 1$.

The degradation from finite laser spot size YOC_b can be approximated through a power of laser beam to target radius R_b/R_t. This can be shown using full 3D simulations of an ensemble of OMEGA implosions driven with different laser beam radii chosen to produce large-amplitude 3D illumination nonuniformities by underfilling the target surface [32]. The degradation from these 3D perturbations can be approximated as

$$\mathrm{YOC}_b \sim (R_b/R_t)^{\gamma} \qquad (5)$$

with $\gamma \approx 2.4$ in 3D simulations, but here, as for all the other degradations, the exponent γ is determined by the mapping to the data.

The degradation from hydrodynamic effects YOC_h depends on the growth of instabilities, which are not captured in the 1D codes, but they depend on 1D parameters such as the shell adiabat $\alpha_F = P_A/P_F$ (ratio of the ablation pressure to the Fermi degenerate pressure), the in-flight aspect ratio IFAR, and convergence ratio C_R [33–36]. In particular, for short-wavelength perturbations such as laser imprinting and surface roughness, the penetration of the Rayleigh-Taylor bubble front relative to the target thickness represents the critical figure of merit, which is proportional to the IFAR, and it is reduced by the ablation velocity, which depends on the adiabat [37]. A functional relation of simulated 1D parameters that best maps the measured yield of the large OMEGA database is constructed by combining the parameters IFAR and α_F into a single parameter $I_\alpha \equiv [(\alpha_F/3)^{1.1}/(\mathrm{IFAR}/20)]$ as indicated in Ref. [34,37]. Since IFAR and α_F are parameters governing primarily the growth of short-wavelength modes, the convergence ratio C_R is added to better account for the degradation from low- and midmode asymmetries. To account for inaccuracies in modeling shock transit, the shell thickness is included through the dimensionless parameter $\hat{D} \equiv R_{\mathrm{out}}/R_{\mathrm{in}}$ representing the ratio between the outer and inner shell radius. Therefore YOC_h is approximated as $\mathrm{YOC}_h \sim I_\alpha^{\eta} C_R^{\omega} \hat{D}^{\varepsilon}$.

At sufficiently large adiabats and low IFARs, implosions become stable to short-wavelength modes, and the benefits of higher adiabat and low IFAR are expected to decrease [34]. Therefore, a piecewise value of η is used above and below a critical value (I_{crit}) of I_α. The final form of the hydrodynamic degradation is then written as

$$\mathrm{YOC}_h \sim \hat{I}_\alpha^{\eta} C_R^{\omega} \hat{D}^{\varepsilon}, \qquad (6)$$

where $\hat{I}_\alpha = I_\alpha/I_{\mathrm{crit}}$ and $\eta = \eta_< \Theta(1-\hat{I}_\alpha) + \eta_> \Theta(\hat{I}_\alpha - 1)$ with $\Theta(x)$ representing the Heaviside step function.

By combining all the degradation mechanisms, the overall measured yield degradation can be expressed as

$$\mathrm{YOC}^{\mathrm{exp}} \sim \hat{I}_\alpha^{\eta} C_R^{\omega} \hat{D}^{\varepsilon} \theta_{\mathrm{T}}^{\delta} \theta_{\mathrm{D}}^{\nu} \xi_{\mathrm{He}}^{\phi} \hat{R}_T^{\mu} (R_b/R_t)^{\gamma}. \qquad (7)$$

The power indices in Eq. (7) are determined by χ^2 minimization over the entire OMEGA implosion database and the two threshold parameters $R_T^{\min}$, I_{crit} were chosen to minimize the cross-validation error. The results are summarized in Table I including the 95% confidence level for each index. Leave-one-out cross validation was carried out to assess the prediction error in order to minimize the risk of overfitting.

TABLE I. Power indices and confidence intervals for all the degradation terms as a result of fitting the model in Eq. (7) to the OMEGA database.

Parameter	Power index	95% confidence interval
$\hat{R}_T^{\mu}$	$\mu = -1.44$	$\mu = -1.61..-1.28$
	$R_T^{\min} = 1.14$	
ξ_{He}^{ϕ}	$\phi = 1.39$	$\phi = 1.25..1.54$
$\theta_{\mathrm{T}}^{\delta}$	$\delta = 1.97$	$\delta = 1.00..2.90$
$\theta_{\mathrm{D}}^{\nu}$	$\nu = 1.16$	$\nu = 0.54..1.79$
$(R_b/R_T)^{\gamma}$	$\gamma = 2.97$	$\gamma = 2.72..3.24$
$\hat{I}_\alpha^{\eta}$	$\eta_< = 1.06$	$\eta_< = 0.91..1.21$
	$\eta_> = 0.45$	$\eta_> = 0.40..0.49$
	$I_{\mathrm{crit}} = 0.8$	
C_R^{ω}	$\omega = -0.97$	$\omega = -1.05..-0.89$
$\hat{D}^{\varepsilon}$	$\varepsilon = -3.35$	$\varepsilon = -4.11..-2.58$

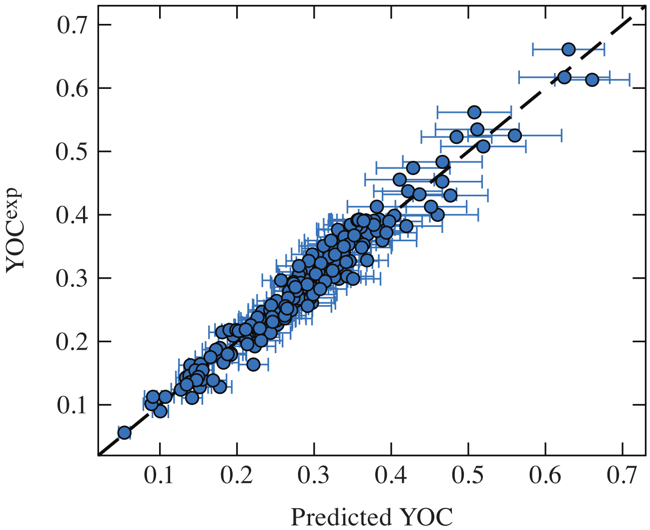

FIG. 1. Measured YOC versus that predicted by the mapping model [Eq. (7)] with the power indices given in Table I. The horizontal error bars represent the uncertainty in measured T_i asymmetry and fuel composition.

Figure 1 shows the overall accuracy of the mapping by plotting the left-hand side of Eq. (7) $\mathbf{Y}^{\text{exp}}$ versus the mapping on the right-hand side. Each dependence can be visualized by isolating the corresponding **YOC** and comparing with the power law approximation

$$\mathbf{YOC}_j^{\text{exp}} \equiv \frac{\mathbf{YOC}^{\text{exp}}}{\Pi_{i\neq j}\mathbf{YOC}_i} \rightarrow \mathbf{YOC}_j. \tag{8}$$

The plots in Fig. 2 show the comparison in Eq. (8) for each dependency.

General conclusions can be readily extracted from this analysis. First, the degradation from the $\ell = 1$ is as predicted by the 3D simulations with a power index $\mu \approx -1.44$ and a threshold factor $R_T^{min} = 1.14$ as expected from the T_i measurement error. Such a good agreement with the simulations confirms the accuracy of the mapping technique to extract the correct trends from the data. Reasonable agreement with 1D simulated degradation due to ^{3}He accumulation is indicated by $\phi \approx 1.39$ close to unity. Furthermore, the degradation in two extremely long fill age targets (45 and 90 days) is well predicted as shown by the two points furthest to the left on Fig. 2(b), adding confidence that the model is correctly accounting for the effect of ^{3}He accumulation. As a result of this analysis, OMEGA shot 96806 was designed with the shortest ever fill age of 3 days, achieving the highest performance on OMEGA to date with a neutron yield of 1.53×10^{14} and an areal density of 157 ± 15 mg/cm^2 at a laser energy of 27.3 kJ. Shot 96806 was subsequently repeated with a fill age of 8 days (shot 96808) resulting in a 14% reduction in fusion yield, as predicted by the statistical model (13%). Another conclusion can be drawn about the

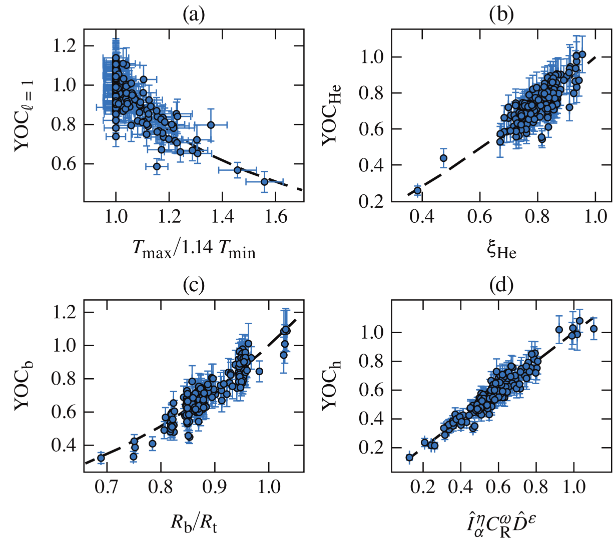

FIG. 2. The individual degradations due to (a) $\ell = 1$ mode, (b) ^{3}He accumulation in the vapor, (c) finite beam size, and (d) hydrodynamic instabilities extracted from the OMEGA database according to Eq. (8). The dashed lines indicate the power laws from the model; the power indices are given in Table I.

isotopic composition of the DT ice layer as maximizing the term $\theta_T^{1.97}(1-\theta_T)^{1.16}$ gives the optimal tritium concentration at $\theta_T \approx 0.6$. The mapping to data reveals a strong R_b/R_t correlation with a power index of $\gamma = 2.97$ which is stronger than indicated by 3D simulations of the beam mode in Ref. [32]. Furthermore, the highest performing implosions with $R_b/R_t \approx 0.87$ show a significant (35%) degradation from this mechanism, whereas post-shot 3D simulations show negligible degradation due to the beam mode. This indicates that new physics is at play, which is an active area of research, and it can include new sources of nonuniformities from the laser beam geometry as well as 1D physics model deficiencies most likely related to the reduction of cross-beam energy transfer when $R_b < R_t$. Lastly, the mapping model indicates strong degradation due to hydrodynamic effects ($\mathbf{YOC}_h$) at low adiabat, high convergence and high IFAR [Fig. 2(d)]. The results indicate that the highest yields can only be achieved at high adiabat and low IFAR with the maximum yield occurring at adiabats > 4.5.

An important application of the above results is correcting the measured yield for the effect of the target offset and mispointing [YOC$_{\ell=1}$ in Eq. (3)] as well as DT fill age and ^{3}He buildup [YOC$_f$ in Eq. (4)]. This enables a fair comparison between fusion yields and helps determine the true highest-yield implosion designs. Figure 3 shows the predicted yields in the OMEGA database versus the corrected yields where the above degradations are removed by setting the corresponding YOC terms to unity. The figure shows that, for T_i asymmetries below the threshold

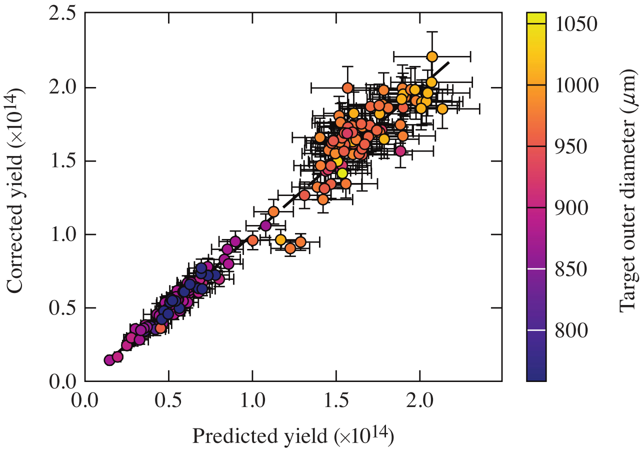

FIG. 3. Measured neutron yield corrected for T_i asymmetry and ^{3}He accumulation versus yield predicted by calculating the degradation given by Eq. (7) with $\xi_{\mathrm{He}} = \hat{R}_T = 1$.

of 14% (within the operational limits of OMEGA) and the shortest possible fill age, the best current designs would achieve a neutron yield of about 2×10^{14}—a 30% improvement over the current record yield. Figure 3 indicates that targets with an outer diameter between 960 μm and 1020 μm provide the best trade-off between increased degradation due to R_b/R_t at larger diameters and reduced energy coupling at smaller diameters. The inferred degradation due to finite beam size in best-performing implosions at a laser spot radius of 415 μm is $\mathrm{YOC}_b \approx 54\%$ to 65% suggesting that mitigating this degradation would lead to neutron yields exceeding 3×10^{14}.

In summary, the major degradation mechanisms in a large database of OMEGA ICF implosions were identified and their effects quantified using the statistical mapping approach. The degradation due to $\ell = 1$ mode from target offset and beam mispointing was found to agree with 3D simulations [31] based on its dependence on the apparent ion temperature asymmetries. The degradation due to ^{3}He accumulation in the vapor region was found to be consistent with 1D simulations, and an optimum fuel composition of 60% tritium was inferred. OMEGA ICF implosions were found to be strongly degraded due to finite laser spot size and hydrodynamic effects at low adiabats and high convergence ratios. Current best-performing designs are predicted to exceed a neutron yield of 2×10^{14} given low $\ell = 1$ asymmetry and short fill ages.

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