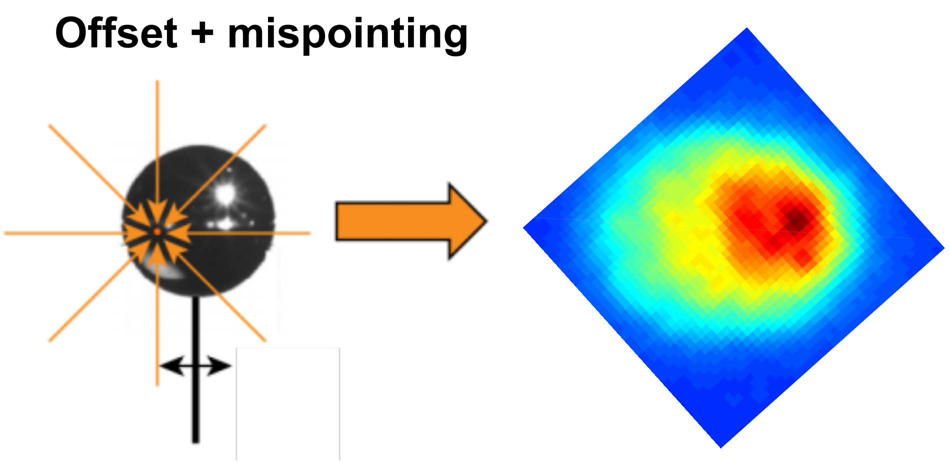
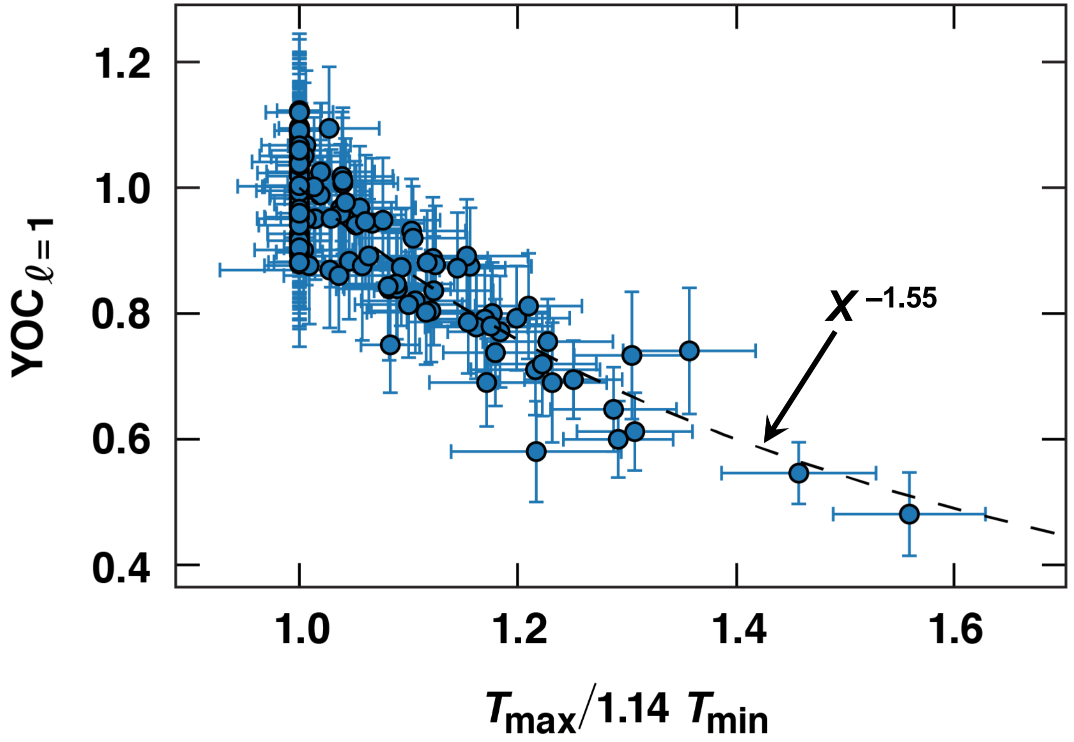
Understanding the Fusion Yield and All of Its Dependencies Using Statistical Modeling of Experimental Data





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Aarne Lees
University of Rochester
Laboratory for Laser Energetics

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Summary

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

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- 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*
  - ℓ = 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

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

* Harding, D. R., and W. T. Shmayda. Fusion Science and Technology 63.2 (2013): 125-131.
Regan, S. P., et al. Nuclear Fusion 59.3 (2018): 032007.
** O. Mannion, KI02.00001, this conference (invited).
*** R. Betti *et al.*, BO09.00011, this conference.

Collaborators

R. Betti, J. P. Knauer, V. Gopalaswamy, D. Patel, R. Epstein, J. Carroll-Nellenback, A. R. Christopherson, K. M. Woo, O. M. Mannion, Z. L. Mohamed, F. J. Marshall, C. Stoeckl, V. Yu. Glebov, S. P. Regan, R. C. Shah, D. H. Edgell, D. Cao, V. N. Goncharov, I. V. Igumenshchev, P. B. Radha, T. J. B. Collins, T. C. Sangster, and E. M. Campbell

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

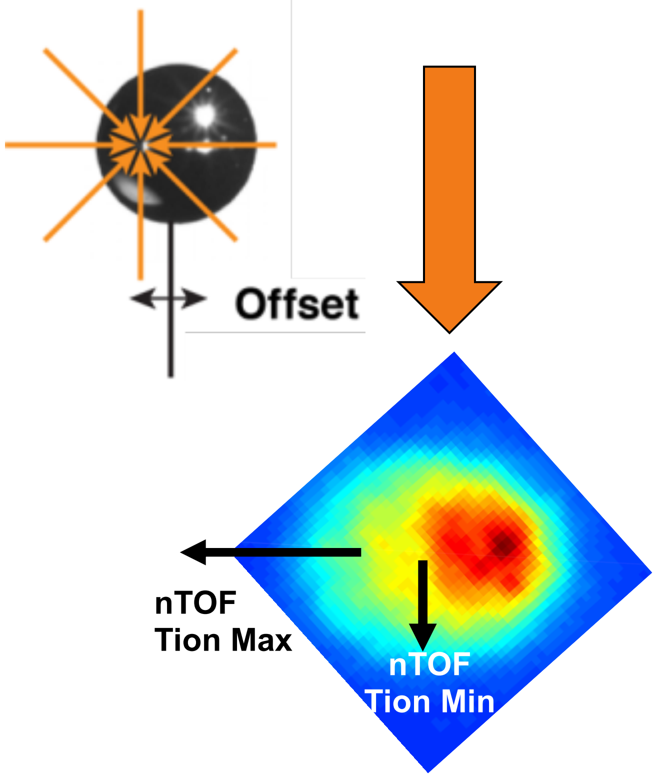
- A physics-based statistical mapping model
- Degradation from the fill age and He^3 accumulation
- Degradation from the $\ell = 1$ mode
- Degradation from R_b/R_t
- Degradation from hydrodynamics: instabilities and/or inaccuracy in physics models
- Predictions of highest yields on OMEGA

A physics-based statistical mapping model

Multiple systematic and random mechanisms degrade the performance of OMEGA implosions

Random degradations

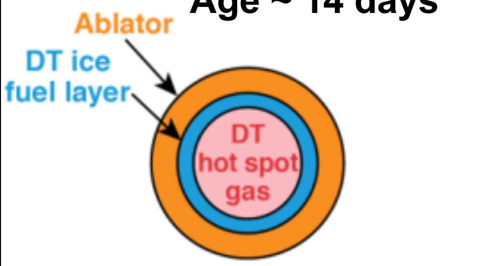
Offset + mispointing



Tion asymmetry = T_{max}/T_{min}

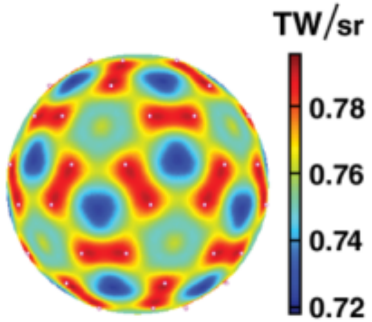
Systematic degradations

Age ~ 14 days



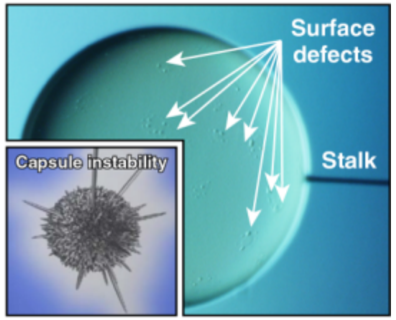
He build up
β-decay damage

Laser absorption pattern

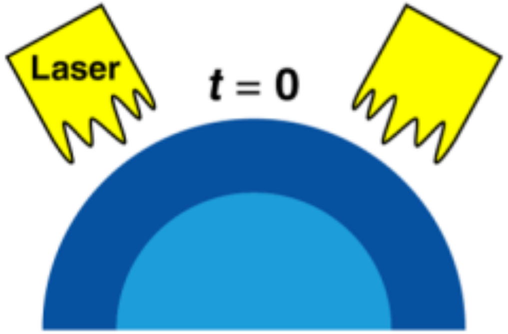


Variation in absorption with CBET

Isolated defects



Laser imprinting



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.* *

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)

Fusion yield → $$Y^{\text{exp}} = F\left[O_{\text{sim}}^{\text{1D}}, I_{\text{other}}, S_{\text{3D}}^{\text{sys}}, R_{\text{3D}}^{\text{ran}}\right]$$

$S_{\text{3D}}^{\text{const}}$ Constant systematic seeds (uncertain)

$S_{\text{3D}}^{\text{var}}$ Variable systematic seeds (e.g., beam size)

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

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

remove because constant

* 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

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

$$\mathrm{YOC}^{\mathrm{exp}} \equiv \frac{Y^{\mathrm{exp}}}{Y^{\mathrm{sim}}_{\mathrm{1D}}}$$

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

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)*

$$\mathrm{YOC}_{\mathrm{exp}} \approx \mathrm{YOC}_{\mathrm{hydro}}\left[O^{\mathrm{sim}}_{1\text{–}\mathrm{D}}\right]\mathrm{YOC}_{\mathrm{fuel}}\mathrm{YOC}_{\ell=1}\mathrm{YOC}_{\mathrm{beam}}\mathrm{YOC}_{\mathrm{res}}$$

Output of 1-D simulations

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

After a global fit (mapping) of data to simulation and selected input parameters, each individual dependence can be visualized by taking out all others

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- Each YOC is approximated by power law dependencies of relevant variables
- For example:

$$\mathrm{YOC_{beam}} \sim \left(\frac{R_\mathrm{b}}{R_\mathrm{t}}\right)^{\gamma}$$

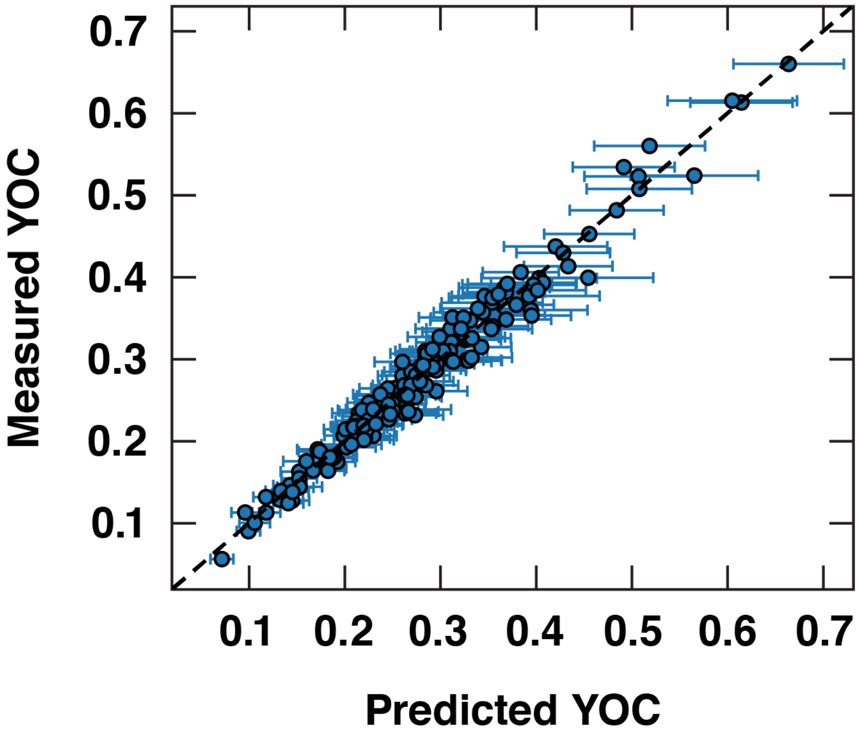
R_b ← Laser-beam radius

R_t ← Target radius

- Nonlinear global fit (mapping) of $\mathrm{YOC^{exp}}$ to all variables produces exponents and confidence levels
- Each individual dependence can be visualized by isolating it from all others

$$\mathrm{YOC}_j^{\mathrm{exp}} \equiv \frac{\mathrm{YOC^{exp}}}{\prod_{i\neq j} YOC_j} \longrightarrow YOC_j$$

Global fit



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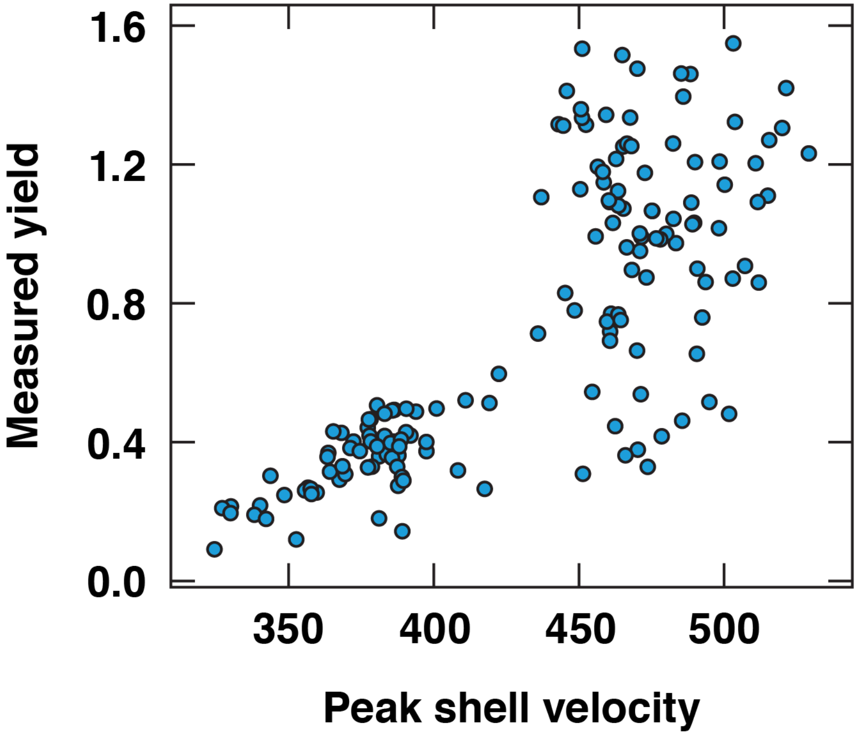
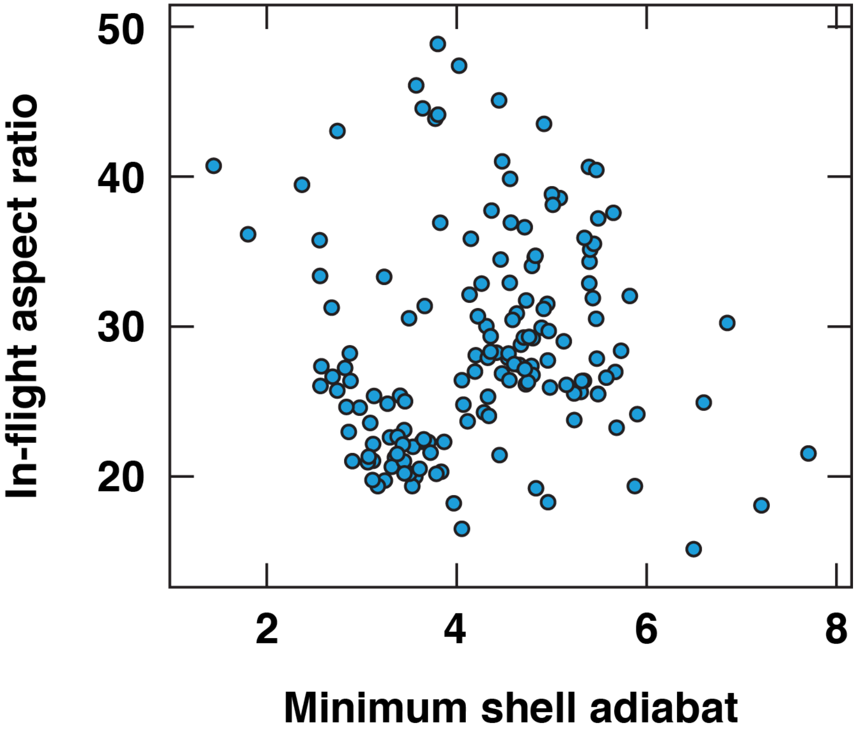
Generalizing model predictions to new designs requires a training set with a large variety of physical conditions





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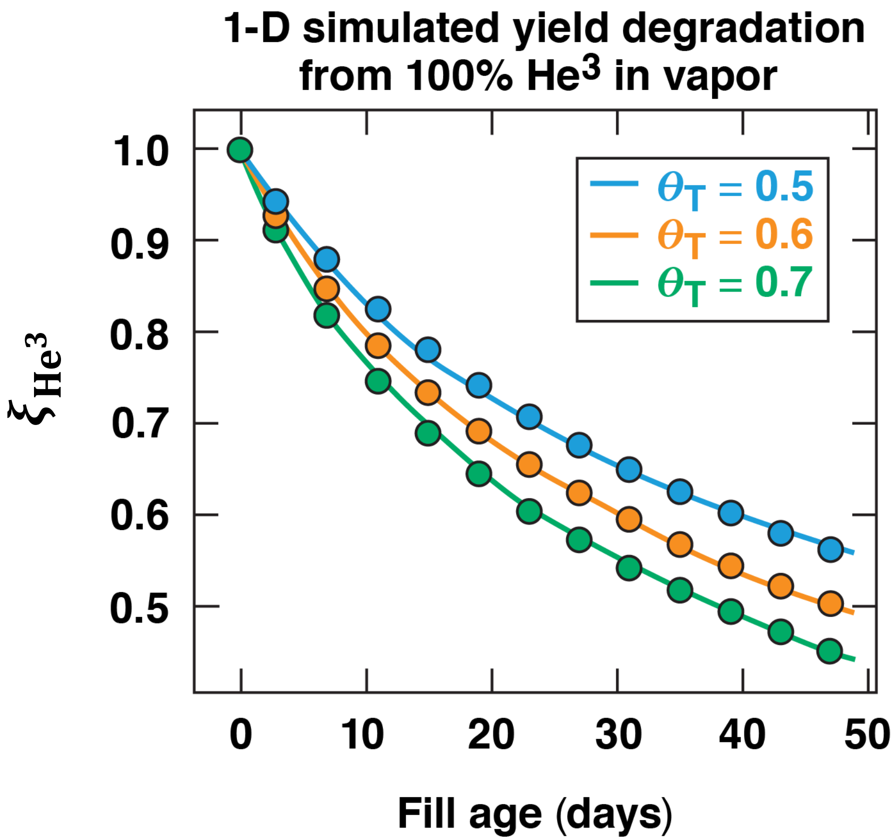
- Fill age ranging from 3 to 97 days
- T_{max}/T_{min} reaching as high as 1.7
- R_b/R_t ranging from 0.69 to 1.05

Degradation from tritium radiation damage and He^3 accumulation

He^3 accumulation and β-radiation damage of ablator* are possible degradation mechanisms; fuel composition can be chosen to optimize performance

- In general: $\mathrm{YOC_{fuel}} = F\left[\theta_\mathrm{T}, \theta_\mathrm{D}, t_\mathrm{age}\right]$
  - θ_T = ice tritium fraction
  - θ_D = ice deuterium fraction
  - t_{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

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



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* Harding, D. R., and W. T. Shmayda. Fusion Science and Technology 63.2 (2013): 125-131.
Regan, S. P., et al. Nuclear Fusion 59.3 (2018): 032007.

Maximizing YOC_{fuel} provides the optimum fuel composition for a given fill age

- General form

$$\mathrm{YOC_{fuel}} = F\left[\theta_{\mathrm{T}}, \theta_{\mathrm{D}}, \xi_{\mathrm{He}^3}\right]$$

- Monotonic power law dependences are assumed

$$\mathrm{YOC_{fuel}} = \theta_{\mathrm{T}}^{\delta}\theta_{\mathrm{D}}^{\mathrm{v}}\xi_{\mathrm{He_3}}^{\phi} \qquad \theta_D = 1 - \theta_T$$

- If $v\delta > 0$ and $\xi_{\mathrm{He_3}} = 1$ (shot right after fill), optimum fuel composition occurs for

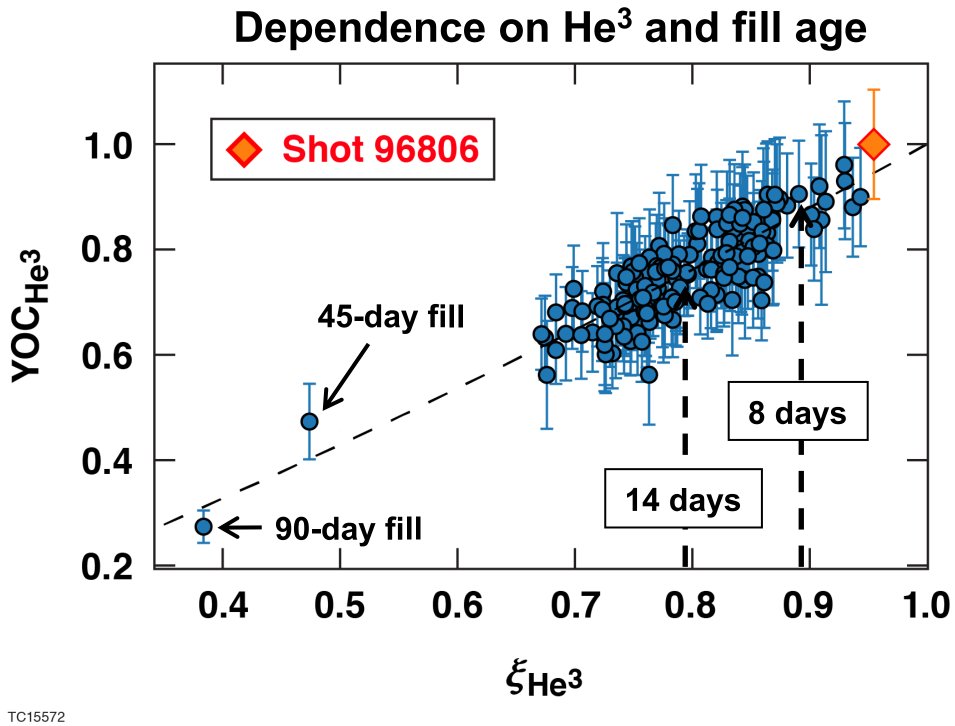
$$\max\left[\theta_{\mathrm{T}}^{\delta}(1-\theta_T)^{\mathrm{v}}\right]$$

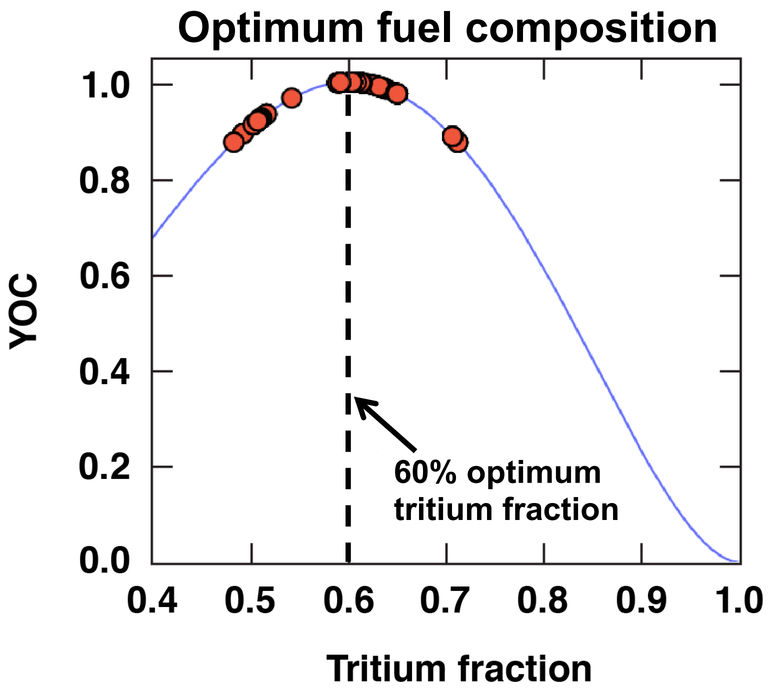
The fill-age degradation is slightly faster than 1-D code predictions from 100% He^3 accumulation in the vapor region; optimum fuel composition occurs at 60% tritium fraction

- Mapping to data:

$$\mathrm{YOC_{fuel}} = \theta_{\mathrm{T}}^{2.2}\theta_{\mathrm{D}}^{1.4}\xi_{\mathrm{He^3}}^{1.2}$$

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

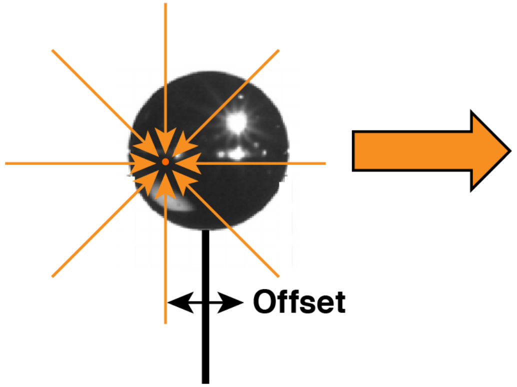




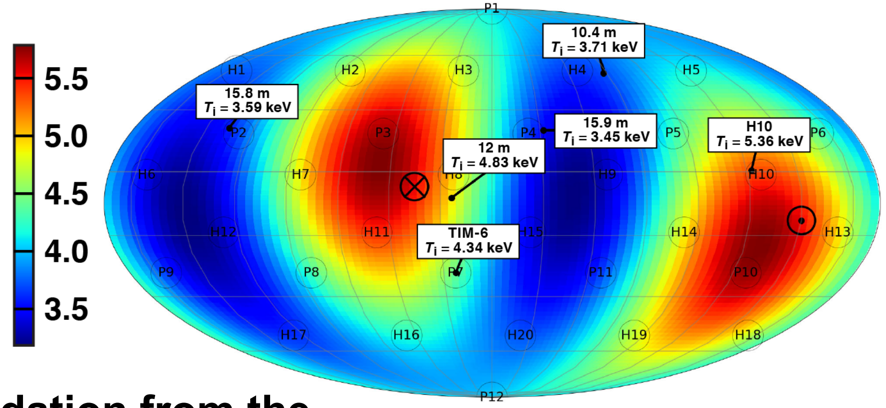
Optimum fuel composition occurs at 60% tritium fraction

Degradation from offset and mispointing

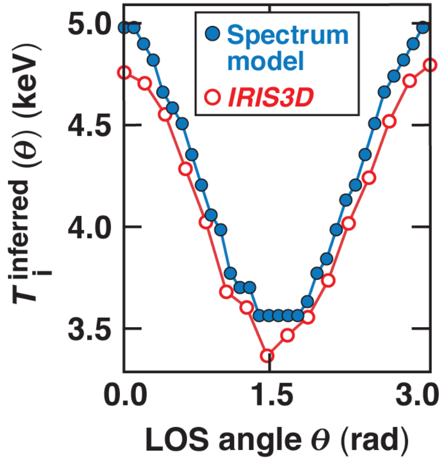
The effects of the ℓ = 1 mode from offset and mispointing are assessed for each shot through the measured T_i asymmetries



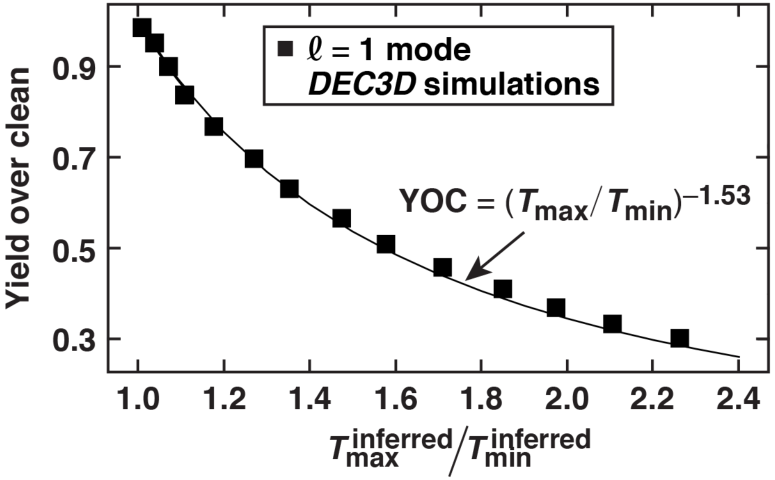
OMEGA 6-LOS measurements of T_i



ℓ = 1 mode leads to large apparent T_i excursion



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



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*K. M. Woo *et al.*, Phys. Plasmas 25, 102710 (2018); 27, 062702 (2020).
LOS: line of sight

The yield degradation from the ℓ = 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 ~300 eV (~10%)

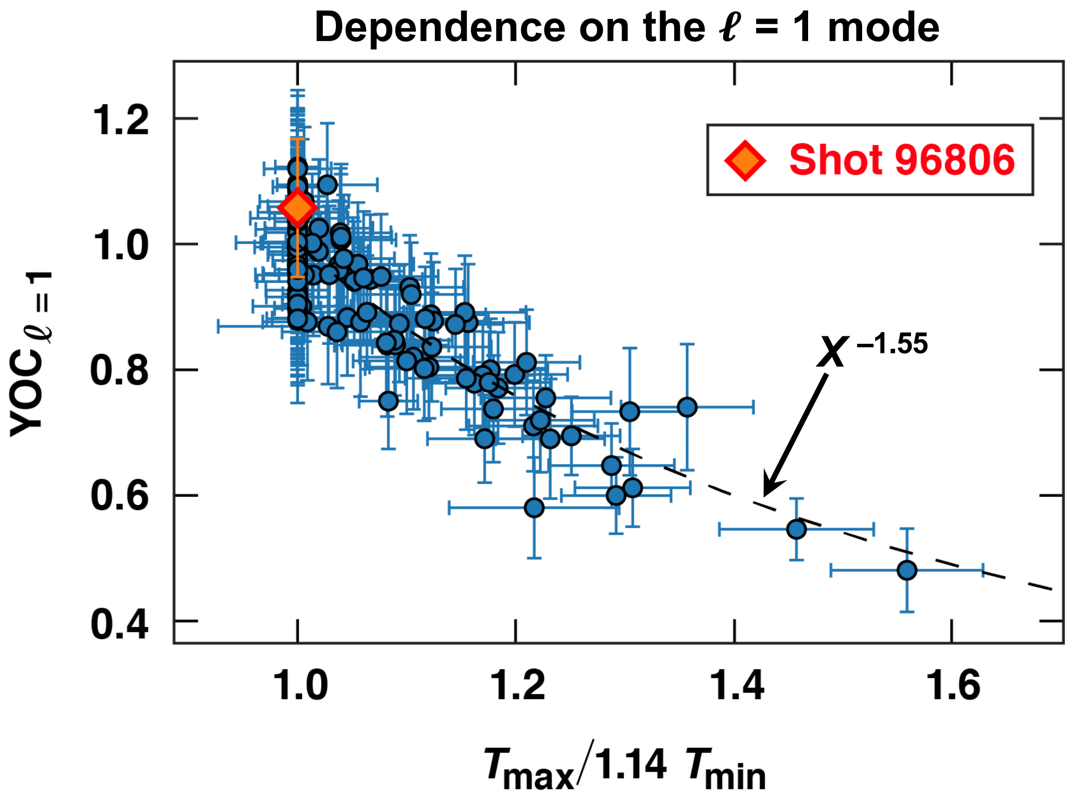
- Power law approximation

$$\mathrm{YOC}_{\ell=1} \approx \min\left[1, \frac{\hat{T}_R^{\min}}{\hat{T}_R}\right]^{-\mu} \quad \hat{T}_R = \frac{T_{\min}}{T_{\max}}$$

- Mapping to data:

μ = 1.55 and $\hat{T}_R^{\min} \approx 1.14$

- Note the good agreement with 3-D simulations (μ_{sim} = 1.53) and $\hat{T}_R^{\min}$ consistent with measurement error (~10%)



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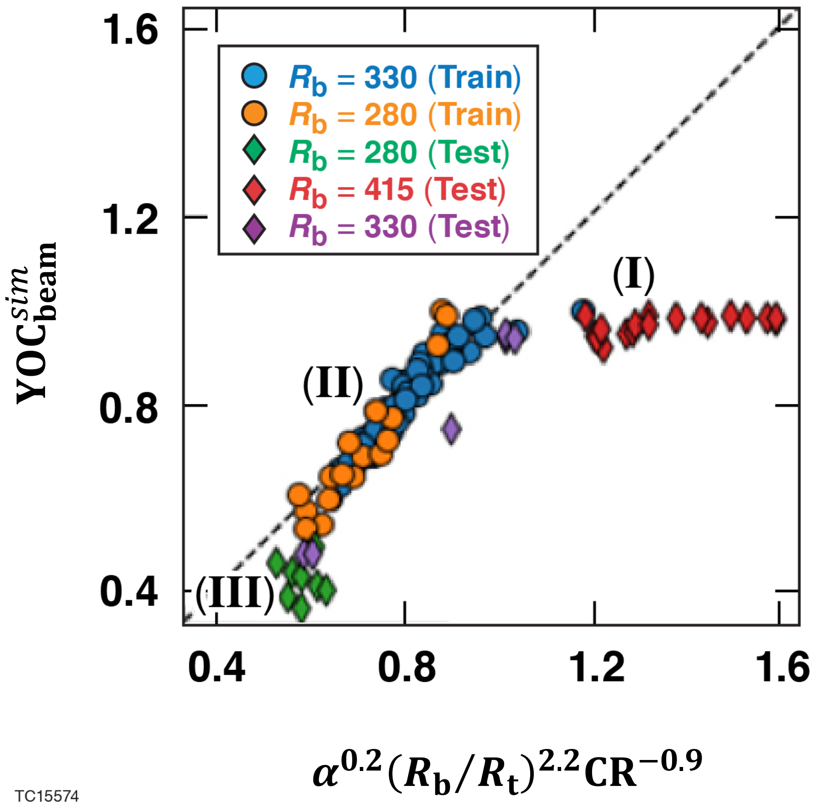
*O. Mannion, KI02.00001, this conference (invited).

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
    $$\mathrm{YOC_{beam}} \approx 1$$
  - II. Yield is degraded as a power law
    $$\mathrm{YOC_{beam}} \approx (R_b/R_t)^{2.2}$$
  - III. Yield degrades faster than power law when the shell is broken up

3-D simulated yield degradation from Rb/Rt **



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* I. Igumenshchev et al, Phys. Plasmas 23, 052702 (2016)
** 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

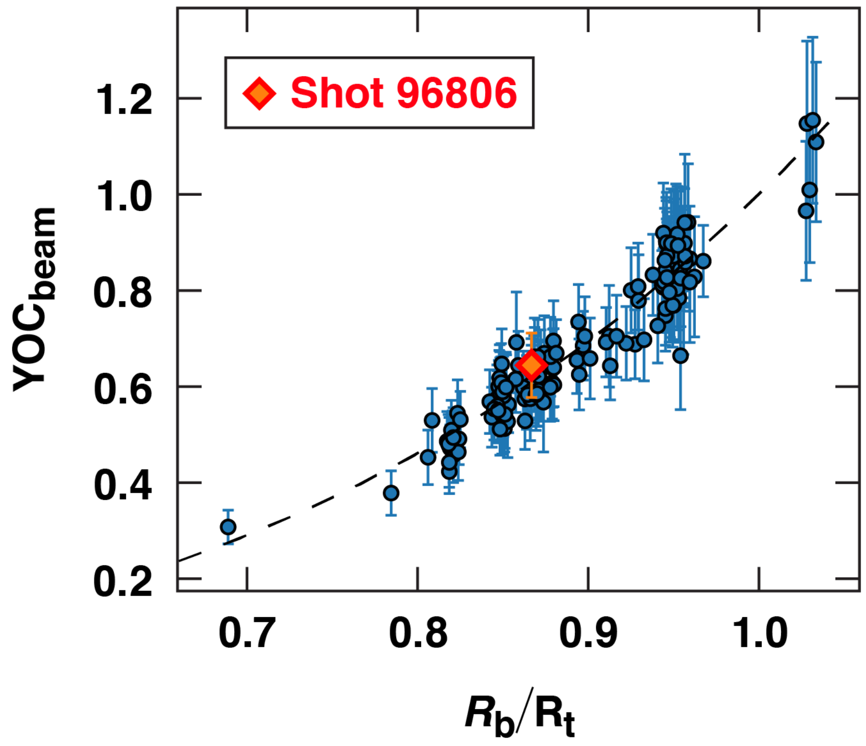
$$\mathrm{YOC_{beam}} \approx \left(\frac{R_\mathrm{b}}{R_\mathrm{t}}\right)^{3.4}$$

- Large yield degradation comes from finite beam size in the best-performing implosion (shot 96806 with $R_b/R_t = 0.86$)

$$\mathrm{YOC_{beam}^{96806}} \approx 0.61$$

- 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.

Dependence on Rb/Rt



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Dedicated experiments with varying Rb/Rt 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**

$$\mathrm{YOC_{hydro}} = \mathrm{YOC_H}\left[\alpha_{\mathrm{1D}}^{\mathrm{sim}}, \mathrm{IFAR}_{\mathrm{1D}}^{\mathrm{sim}}, \mathrm{CR}_{\mathrm{1D}}^{\mathrm{sim}}, t_{\mathrm{coast}}^{\mathrm{sim}}, t_{\mathrm{shock}}^{\mathrm{sim}}\right]$$

- **Adiabat $\alpha \Rightarrow$ stability of short and mid modes**
- **In-flight aspect ratio (IFAR) $\Rightarrow$ stability of short wavelength modes**
- **Convergence ratio $\Rightarrow$ stability of all modes (related to α)**
- **Coasting time $\Rightarrow$ decompression and deceleration phase instabilities**
- **Shock breakout time $t_{\mathrm{sb}} \Rightarrow$ 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**

$$\mathrm{YOC_{Hydro}} \sim \alpha^{\varepsilon} T_{\mathrm{rel}}^{\omega} T_{\mathrm{c}}^{\eta}$$

Adiabat **Relative shock breakout time** **Dimensionless coasting time**

Dimensionless coasting time $T_c \sim \frac{t_{V_{\mathrm{imp}}^{\max}}}{t_{\mathrm{bang}}}$

Relative shock breakout time

$$T_{rel} = \frac{R_0/V_{\mathrm{imp}}}{t_{\mathrm{sb}}(A_0/16) + \left(t_{V_{\mathrm{imp}}^{\max}} - t_{\mathrm{sb}}\right)} \sim \mathrm{IFAR}^{-0.2}\mathrm{CR}^{-0.25}$$

Shock breakout time

Initial aspect ratio

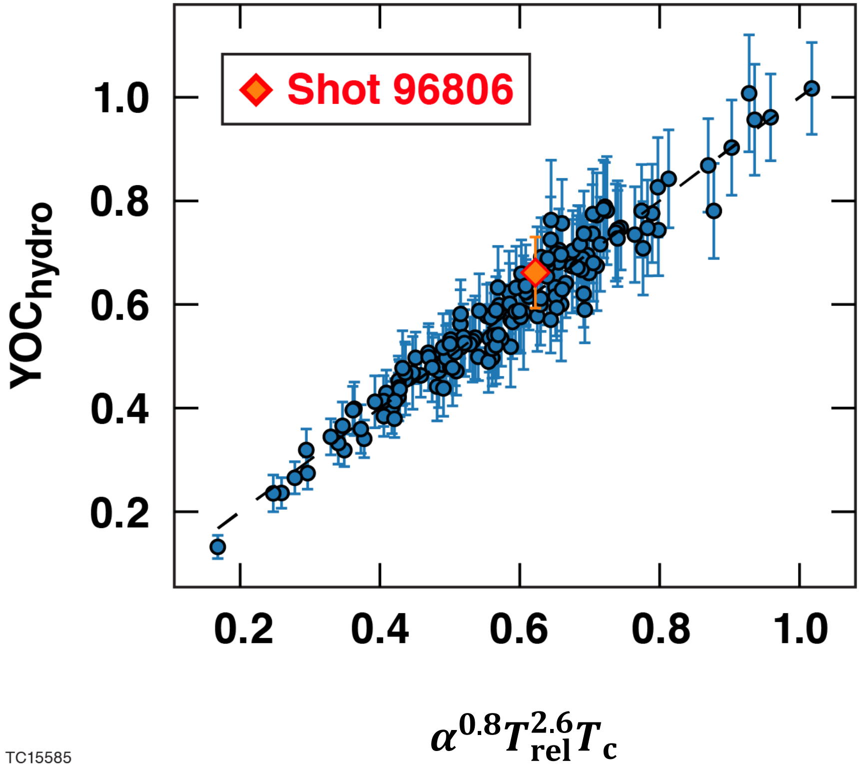
Time of peak implosion velocity

Mapping to the data reveals a trend of strong yield degradation at low adiabats, high IFAR and high CR

- **Mapping to data:** $\mathrm{YOC_{hydro}} \approx \alpha^{0.8} T_{\mathrm{rel}}^{2.6} T_{\mathrm{c}}$
- **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**

$$\mathrm{YOC_{hydro}^{96806}} \approx 0.65$$

Dependence on hydrodynamic stability parameters



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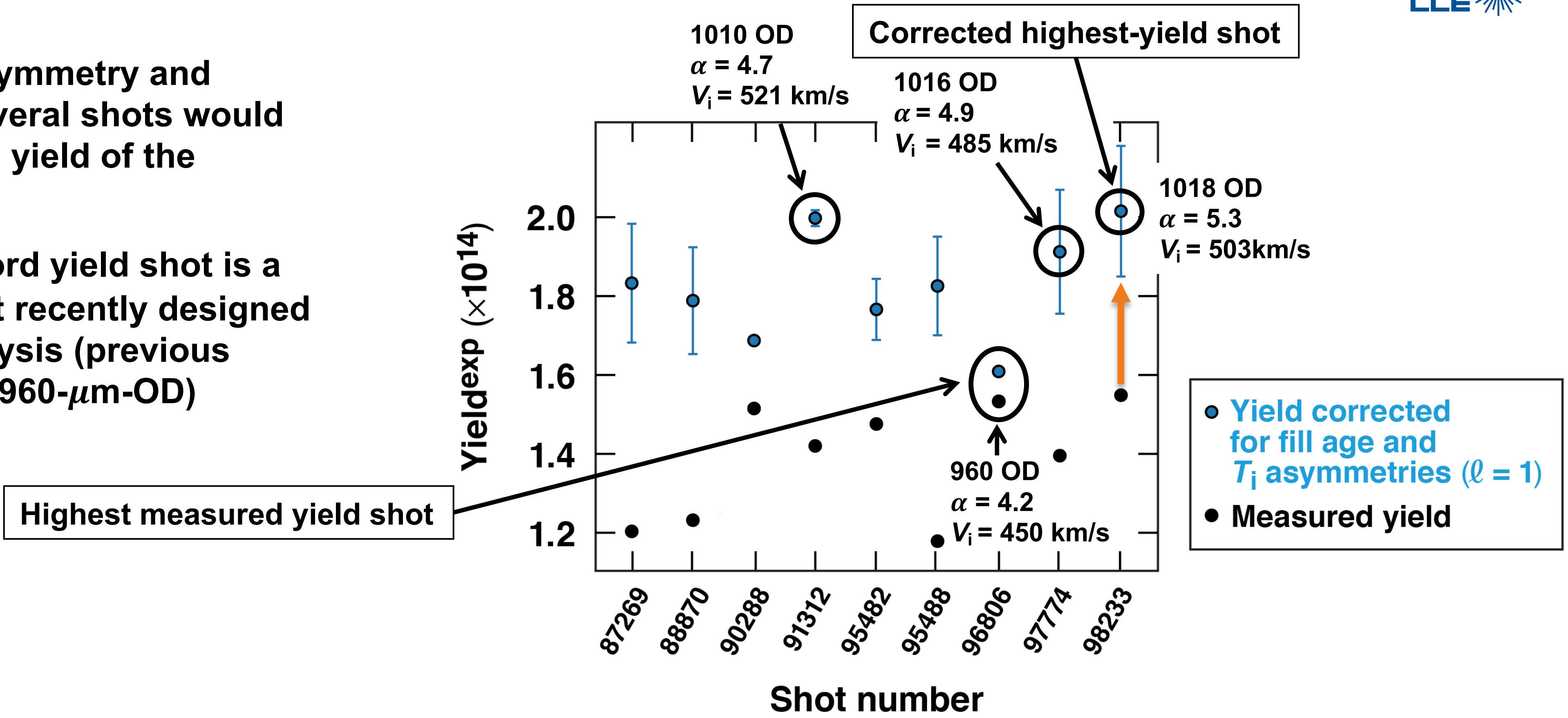
The measured yield of past experiments can be corrected for fill age and ℓ = 1 degradation for valid comparison to identify true highest-yield shot

- Given low ℓ = 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-μm-OD target recently designed based on this analysis (previous record shot was a 960-μm-OD)



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These corrections are used to guide future design choices. Increasing the yield of OMEGA best performer to 2×10^{14} (at fixed ρR=160mg/cm^2) hydroscales to ~0.8MJ of fusion yield at 2MJ of symmetric illumination

Summary/Conclusions

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- 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
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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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