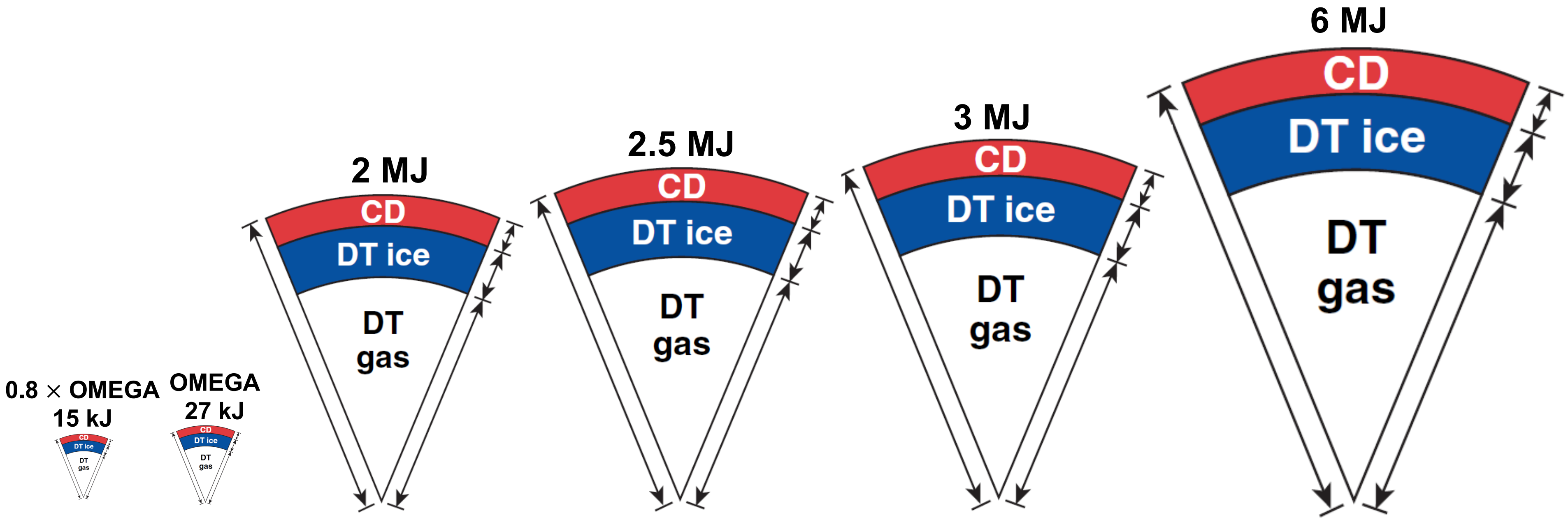
Exploring Pathways to Hydro-Equivalent Ignition on the OMEGA Laser



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Summary

There are plausible scenarios based on current OMEGA experiments for hydro-scaled ignition at 2 to 6 MJ of symmetric illumination

- **A physics-based mapping model used to predict OMEGA implosion performance can identify possible paths to hydro-scaled ignition at multi-MJ of symmetric illumination**
- **At least three factors can augment implosion performance in hydroscaled targets**
  - **a faster-than-hydro-scaling dependence on size**
  - **larger OD targets to improve the energy coupling**
  - **zooming the laser after the picket**
- **Combining these three effects, there is a plausible path to hydro-scaled ignition at ~2 to 3 MJ of symmetric illumination (assuming LPI degradation remains at the levels of OMEGA)**
- **Lowering the adiabat below $\alpha \sim 4$ would greatly improve performance but is not assumed here**

LPI: laser–plasma instability

Collaborators

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The best-performing OMEGA implosion achieved a normalized Lawson triple product $\chi \approx 0.174 \pm 0.01$, hydroscaled to $\chi \approx 0.74$ for ~2 MJ of laser energy

Shot	Yield	ρR (mg/cm^2)	T_i (keV)	x-ray GMXI R (μm)	τ_{BW} (ps)	P (Gbar)	α	CR R_t/R_{GMXI}	E_L (kJ)
96806	$1.6 \pm 0.1 \times 10^{14}$	160±12 (3 LOS)	4.42±0.3	26.5±1	67±8	65±10	4.2	18	27.25

- **Normalized Lawson parameter**

$$\chi \equiv \rho R_{\mathrm{g/cm^2}}^{0.61} \left(\frac{0.12 Y_{16}}{M_{\mathrm{mg}}^{\mathrm{stag}}}\right)^{0.34}$$

$$\chi_{\mathrm{OMEGA}} \equiv 0.174 \pm 0.01$$

- **Hydro scaling to MJ's of laser energy**

$$\chi = \frac{P\tau}{(P\tau)_{\mathrm{ign}}(T)} \quad \tau \sim R \sim E_{\mathrm{L}}^{1/3}$$

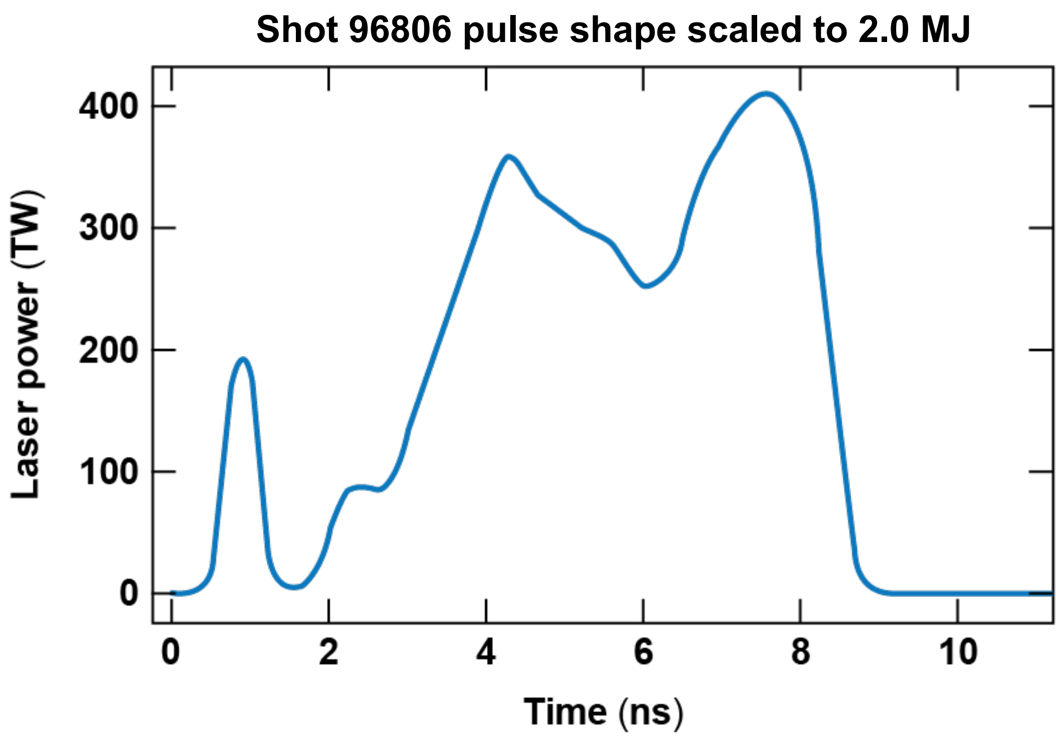
Hydro-equivalent ignition (definition)

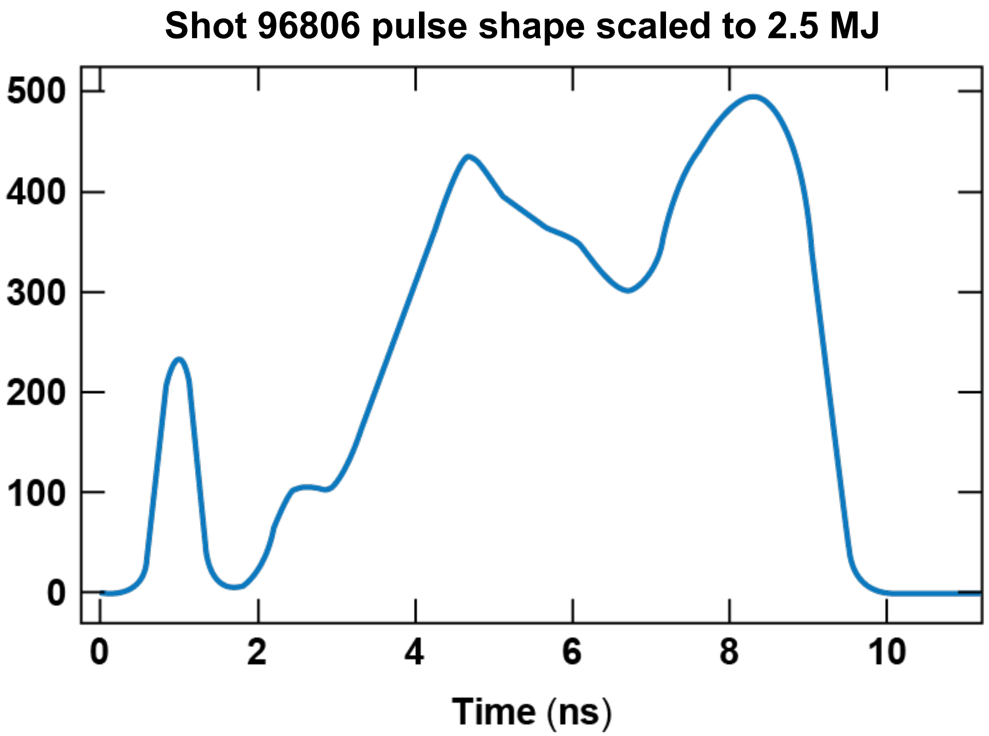
$$\chi_{\mathrm{MJ}} \equiv \chi_{\mathrm{OMEGA}} \left[\frac{E_{\mathrm{L}}(\mathrm{MJ})}{E_{\mathrm{L}}^{\mathrm{OMEGA}}}\right]^{1/3} \Longrightarrow 1$$

E_L	2 MJ	2.5 MJ	3 MJ	6 MJ
χ	0.74	0.8	0.84	1.04

LOS: line of sight

Laser pulse shapes hydro scaled up to 2.5 MJ of laser energy are below the 500-TW limit





TC15577

The mapping model* is a useful tool to uncover trends in the experimental database and identify degradation mechanisms**

$$\mathrm{Yield}_{\mathrm{exp}} \approx \mathrm{Yield}^{1-\mathrm{D}}_{\mathrm{sim}} \underbrace{\mathrm{YOC}_{\mathrm{hydro}}(\alpha, \mathrm{IFAR}, \mathrm{CR})\ \mathrm{YOC}_{\mathrm{He}^3}\ \mathrm{YOC}_{\ell=1}\ \mathrm{YOC}_{R_\mathrm{b}R_\mathrm{t}}\ \mathrm{YOC}_{\mathrm{res}}}$$

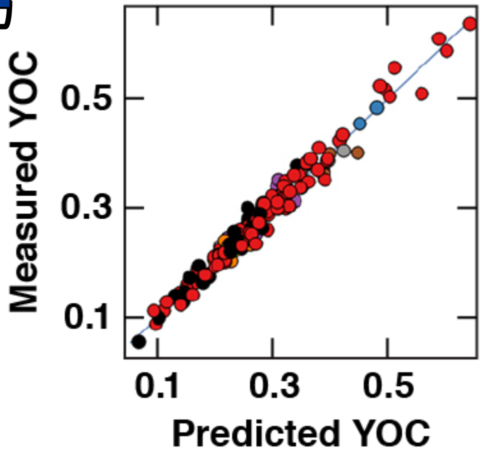
$\mathrm{YOC}_{\mathrm{hydro}}$ = degradation from hydro instabilities, shock mistiming, 1-D physics inaccuracies

$\mathrm{YOC}_{\mathrm{He}^3}$ = degradation from T decay, He^3 contamination, ablator damage from β decay

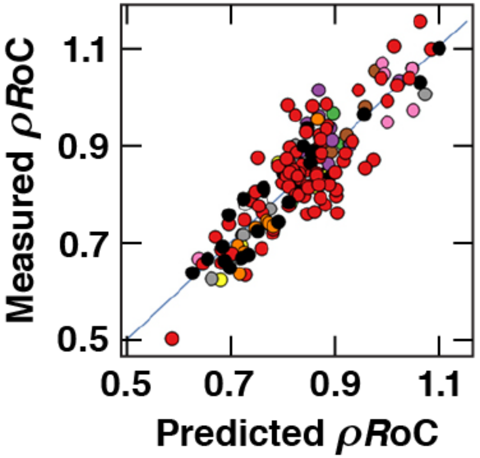
$\mathrm{YOC}_{\ell=1}$ = degradation from target offset and laser mispointing

$\mathrm{YOC}_{\mathrm{beam}}$ = degradation from finite beam size

$\mathrm{YOC}_{\mathrm{res}}$ = residual size scaling



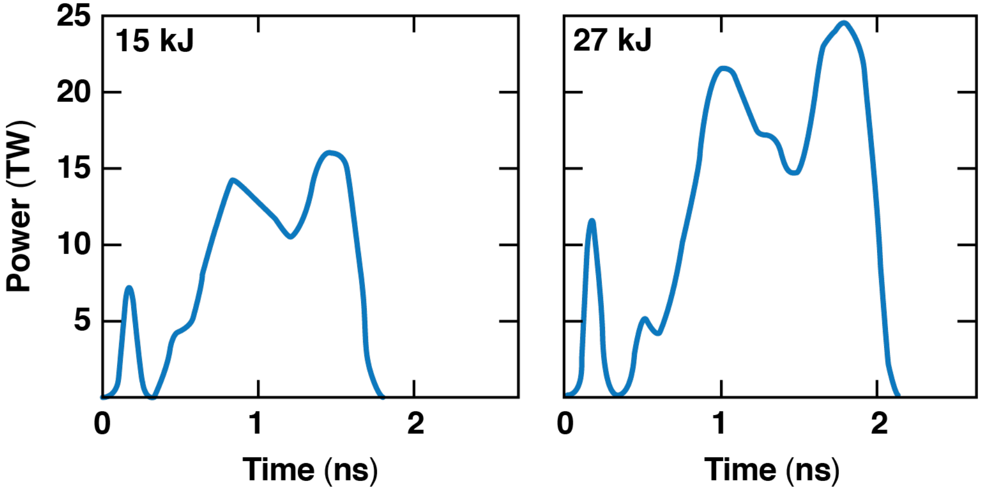
$$\approx \rho R^{1-\mathrm{D}}_{\mathrm{sim}} \underbrace{\rho R\mathrm{oC}_{\mathrm{hydro}}(\mathrm{IFAR}, \mathrm{CR})\ \rho R\mathrm{oC}_{\mathrm{He}^3}\ \rho R\mathrm{oC}_{\ell=1}\ \rho R\mathrm{oC}_{R_\mathrm{b}R_\mathrm{t}}\ \rho R\mathrm{oC}_{\mathrm{res}}}$$



TC15578

* V. Gopalaswamy *et al.*, Nature 565, 581 (2019).
** A. Lees, TI01.00006, this conference (invited).
YOC: yield over clean
IFAR: in-flight aspect ratio
CR: convergence ratio

Dedicated hydro-scaled experiments* on OMEGA seem to indicate that the areal density scales faster than predicted by hydro scaling



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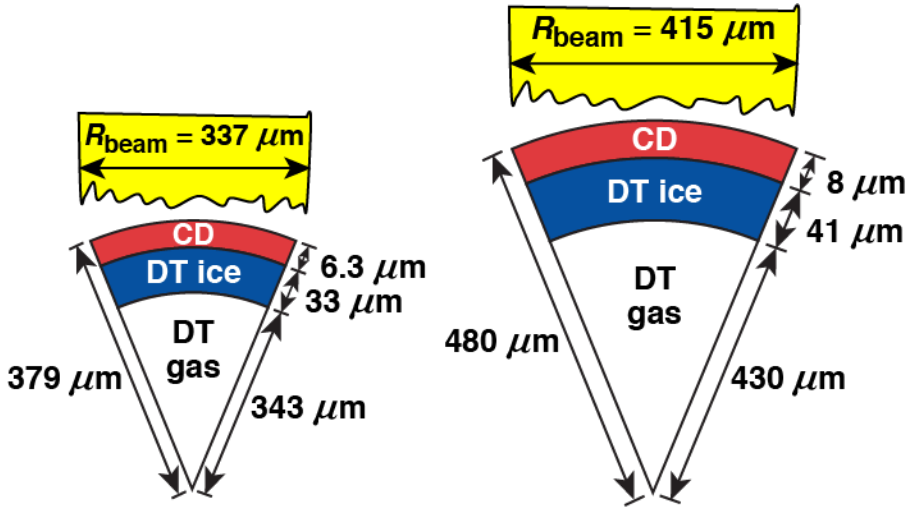

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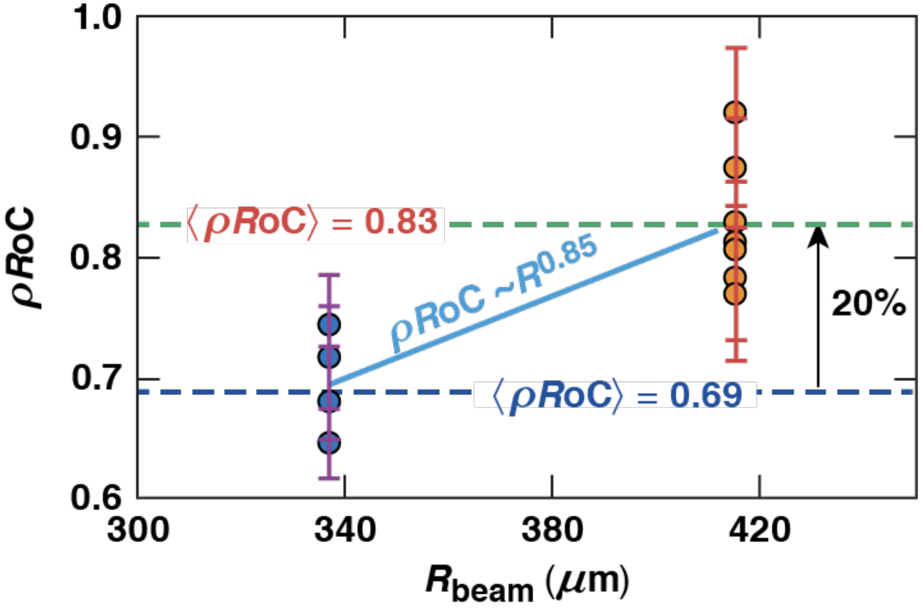
⟨*P*⟩ = 52±9 Gbar

⟨*P*⟩ = 65±10 Gbar



TC15579

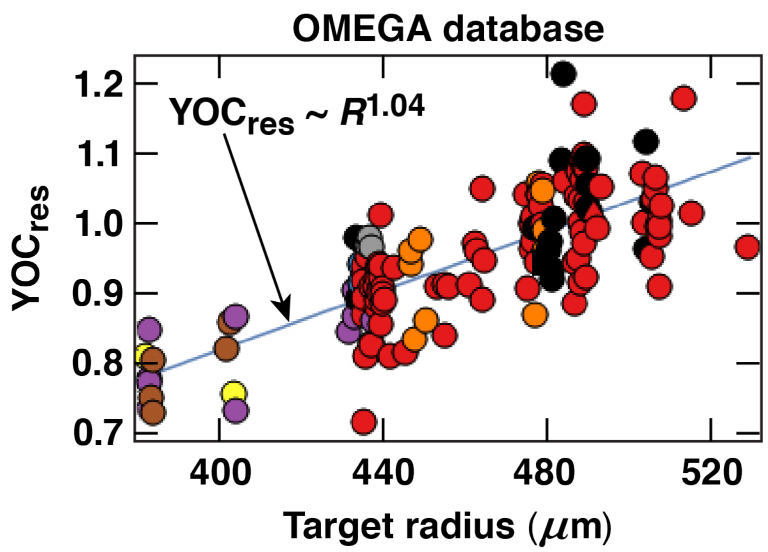
$$\rho RoC = \frac{\rho R_{exp}}{\rho R^{1-D}_{sim}}$$

* C. A. Thomas *et al.*, O09.00010, this conference.
W. Theobald *et al.*, BO09.00012, this conference.

Both the OMEGA implosion database and dedicated hydro-scaled experiments exhibit a size dependence of the fusion yield faster than hydro scaling

$$\mathrm{Yield_{exp}} \approx \underbrace{\mathrm{Yield}^{1-D}_{\mathrm{sim}}}_{\text{1-D code hydro scaling}} \underbrace{\mathrm{YOC_{hydro}}(\alpha, \mathrm{IFAR, CR})\, \mathrm{YOC_{He^3}}\, \mathrm{YOC}_{\ell=1}\, \mathrm{YOC}_{R_b/R_t}}_{\text{Scale invariant}} \underbrace{\mathrm{YOC_{res}}}_{\text{Residual scaling}}$$

$\mathrm{YOC_{res}} \sim R^{1.04 \pm 0.2}$



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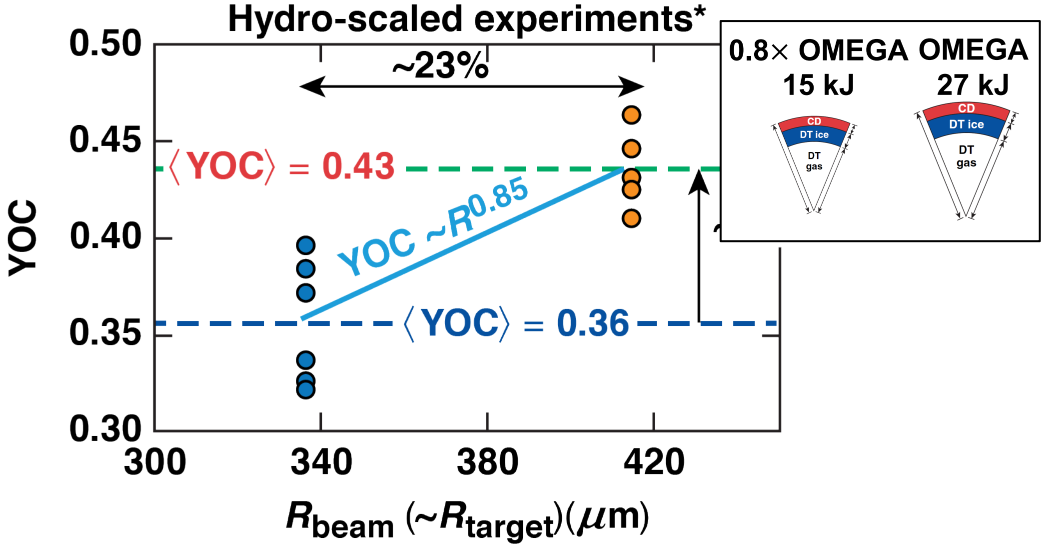


* C. A. Thomas *et al.*, O09.00010, this conference.
W. Theobald *et al.*, BO09.00012, this conference.

The faster-than-hydroscaling size scaling could be sufficient for hydro-equivalent ignition at 3 MJ of symmetric illumination

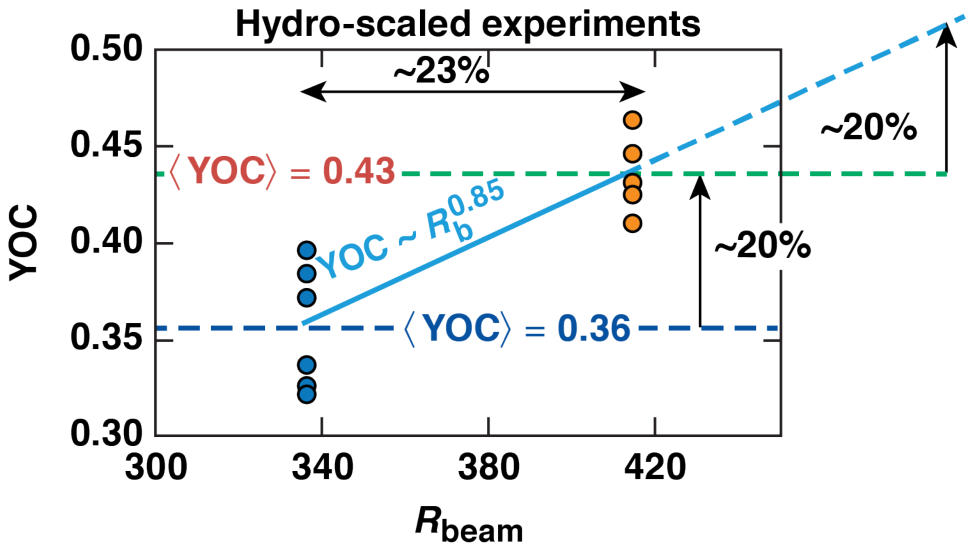
- Possible causes of residual scaling: defects, kinetic effects, radiation preheat, stalk, hot-electron preheat
- Since the origin of this residual size scaling is currently unknown, it is not possible to determine the extent of its validity; a reasonable extrapolation of this residual size scale for another 20%

$$\chi \equiv \rho R^{0.61}_{\mathrm{g/cm^2}} \left(\frac{0.12 Y_{16}}{M^{\mathrm{stag}}_{\mathrm{mg}}}\right)^{0.34} \left(\frac{E_{\mathrm{L}}}{E^{\mathrm{OMEGA}}_{\mathrm{L}}}\right)^{1/3}$$

$$\chi = (1.2 \times \rho R)^{0.61} \left(\frac{0.12 Y_{16} \times 1.2}{M^{\mathrm{stag}}_{\mathrm{mg}}}\right)^{0.34} \left(\frac{E_{\mathrm{L}}}{E^{\mathrm{OMEGA}}_{\mathrm{L}}}\right)^{1/3}$$

$1.2 \times R \Rightarrow 1.7 \times E^{\mathrm{OMEGA}}_{\mathrm{L}} - 47\ \mathrm{J}$ ← Exceeds OMEGA laser energy

$1.2 \times R \Rightarrow \mathrm{YOC} = 0.52$ ρRoC = 1 ← Limit?



E_{L}	2 MJ	2.5 MJ	3 MJ	6 MJ
χ without residual scaling	0.74	0.8	0.84	1.04
χ with residual scaling	0.87	0.94	1.0	1.25

TC15580a

Another path to hydro-equivalent ignition is to improve the performance of OMEGA implosions beyond shot 96086: larger shells lead to higher yields

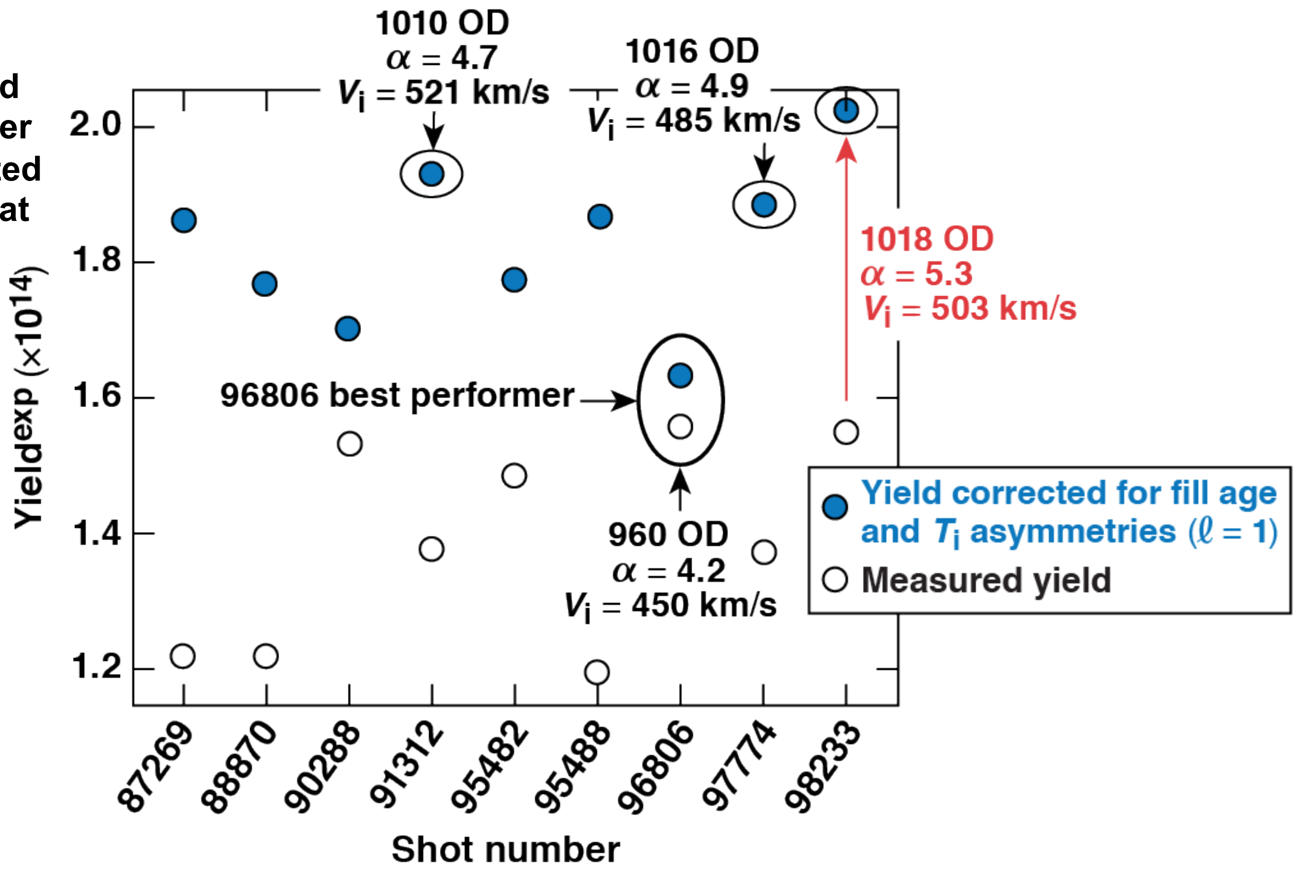
$$\text{Yield}_{\text{exp}} \approx \text{Yield}_{\text{sim}}^{1-\text{D}} \underbrace{\text{YOC}_{\text{hydro}}(\alpha, \text{IFAR}, \text{CR})\ \text{YOC}_{\text{He}^3}\ \text{YOC}_{\ell=1}\ \text{YOC}_{R_b R_t}}\ \text{YOC}_{\text{res}}$$

1-D simulated yield increases at larger OD due to better energy coupling

Larger OD's and V_{imp} lead to larger IFAR compensated by higher adiabat

Assuming yield 2×10^{14} and same ρR

E_L	2 MJ	2.5 MJ	3 MJ	6 MJ
χ without residual scaling	0.79	0.85	0.90	1.14
χ with residual scaling	0.94	1.0	1.07	1.35

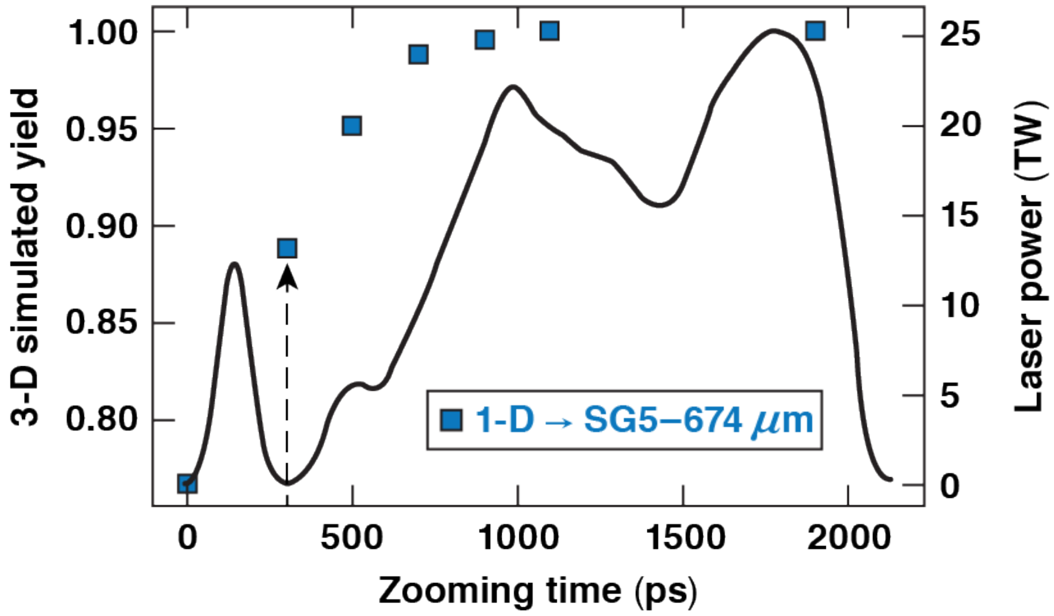


TC15582

Another path to hydro-equivalent ignition is to improve the performance of OMEGA implosions beyond shot 96086: Zooming phase plates lead to higher yields

$$\text{Yield}_{\text{exp}} \approx \text{Yield}_{\text{sim}}^{1-\text{D}}\,\text{YOC}_{\text{hydro}}(\alpha,\ \text{IFAR},\ \text{CR})\ \text{YOC}_{\text{He}^3}\ \text{YOC}_{\ell=1}\ \text{YOC}_{R_\text{b}R_\text{t}}\ \text{YOC}_{\text{res}}$$

3-D *ASTER simulations:**** about 50% of the yield loss comes from nonuniformities seeded during the picket (0.8× smaller beam size is required in *ASTER* for yield degradation)**



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Large loss of yields comes from finite beam size i.e., ratio $R_{\text{beam}}/R_{\text{target}}$

$$\text{YOC}_{\text{beam}} = \left(\frac{R_\text{b}}{R_\text{t}}\right)^{3.4} = 0.5 \text{ for } 1010\ \mu\text{m OD}$$

Zooming after picket (i.e., YOC up 50%)

E_L	2 MJ	2.5 MJ	3 MJ	6 MJ
χ without residual scaling and 1.5× yield	0.90	0.97	1.0	1.3
χ with res scaling and 1.5× yield	1.07	1.16	1.23	1.55

* I. V. Igumenshchev *et al.*, Phys. Plasmas 23, 052702 (2016).
** V. Gopalaswamy *et al.*, GO10.00002, this conference.

Summary/Conclusions

There are plausible scenarios based on current OMEGA experiments for hydro-scaled ignition at 2 to 6 MJ of symmetric illumination

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- **A physics-based mapping model used to predict OMEGA implosion performance can identify possible paths to hydro-scaled ignition at multi-MJ of symmetric illumination**
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