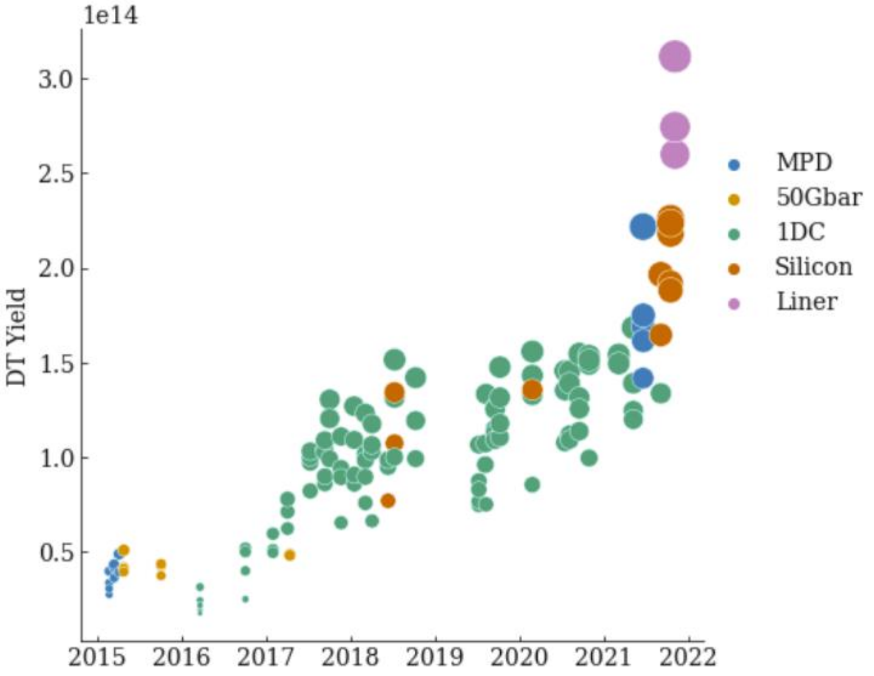
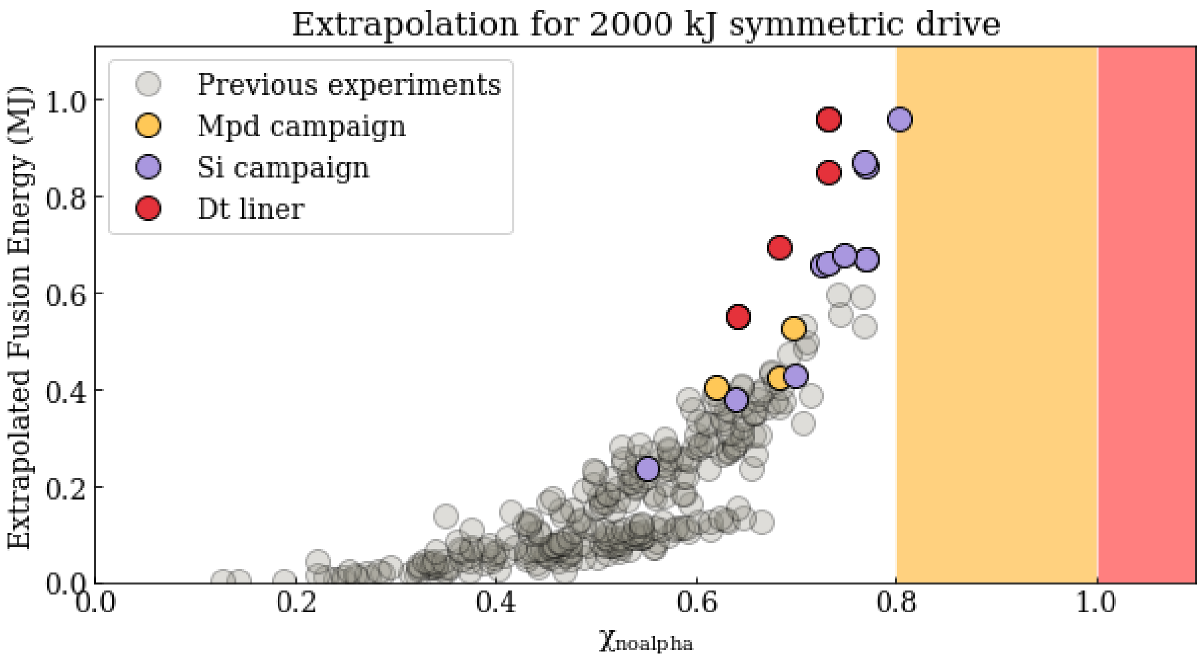
Advances Toward Hydro-Equivalent Ignition in OMEGA Direct-Drive Implosions





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Division of Plasma Physics
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Summary

Record yields and extrapolated Lawson parameters have been achieved on OMEGA

- **Recent implosions have demonstrated yields of 2.3e14, giving $\chi = 0.8$ and 1 MJ of fusion yield at 2 MJ of symmetric drive with over 80 Gbar of pressure**
- **The path toward hydro-equivalent ignition is to maximize fusion yields at constant ρR, and then increase ρR**
- **The statistical model allows for rapid validation of design for increased fusion yields by adjusting for shot-to-shot variations**
- **The use of the multipulse driver (MPD) and mid-*Z*-doped ablators has shown promise in increasing yields through increasing coupling**
- **Increasing ρR is challenging due to the inherently asymmetric nature of the measurement**
- **Once the yield is sufficiently high, the ρR will be increased by optimizing shocks**

Collaborators

R. Betti, J. P. Knauer, D. Patel, A. Lees, K. M. Woo, C. A. Thomas, D. Cao, O. M. Mannion, R. C. Shah, C. J. Forrest, Z. L. Mohamed, C. Stoeckl, V. Yu. Glebov, S. P. Regan, D. H. Edgell, M. J. Rosenberg, I. V. Igumenshchev, P. B. Radha, K. S. Anderson, J. R. Davies, T. J. B. Collins, V. N. Goncharov, K. Chrunetski, W. Theobald, and E. M. Campbell

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S. Sampat, K. A. Bauer, and the System Science Group

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Plasma Science and Fusion Center
Massachusetts Institute of Technology

The performance of OMEGA implosions is assessed through measurements of the neutron yield and areal density

UR LLE

- **Lawson parameter for ICF***

$$\chi_{3\text{-D}} = \frac{\mathrm{n}T\tau}{[\mathrm{n}T\tau]_{\mathrm{ignition}}} \approx \langle \rho R_{\mathrm{g/cm^2}} \rangle_{3\text{-D}}^{0.61} \left[\frac{0.12\ \mathrm{yield}_{16}}{M_{\mathrm{DT\ stag}}^{\mathrm{mg}}} \right]^{0.34}$$

- **Hydrodynamic scaling**

$$\chi \sim P\tau \sim \tau \sim R \sim E_{\mathrm{L}}^{1/3}$$

Scale to 2 MJ of symmetric drive

- **Scaled ignition**

For ignition

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

About 4.2× for 2 MJ

Hydro-equivalent ignition:
χ = 1 at ≈ 2 MJ

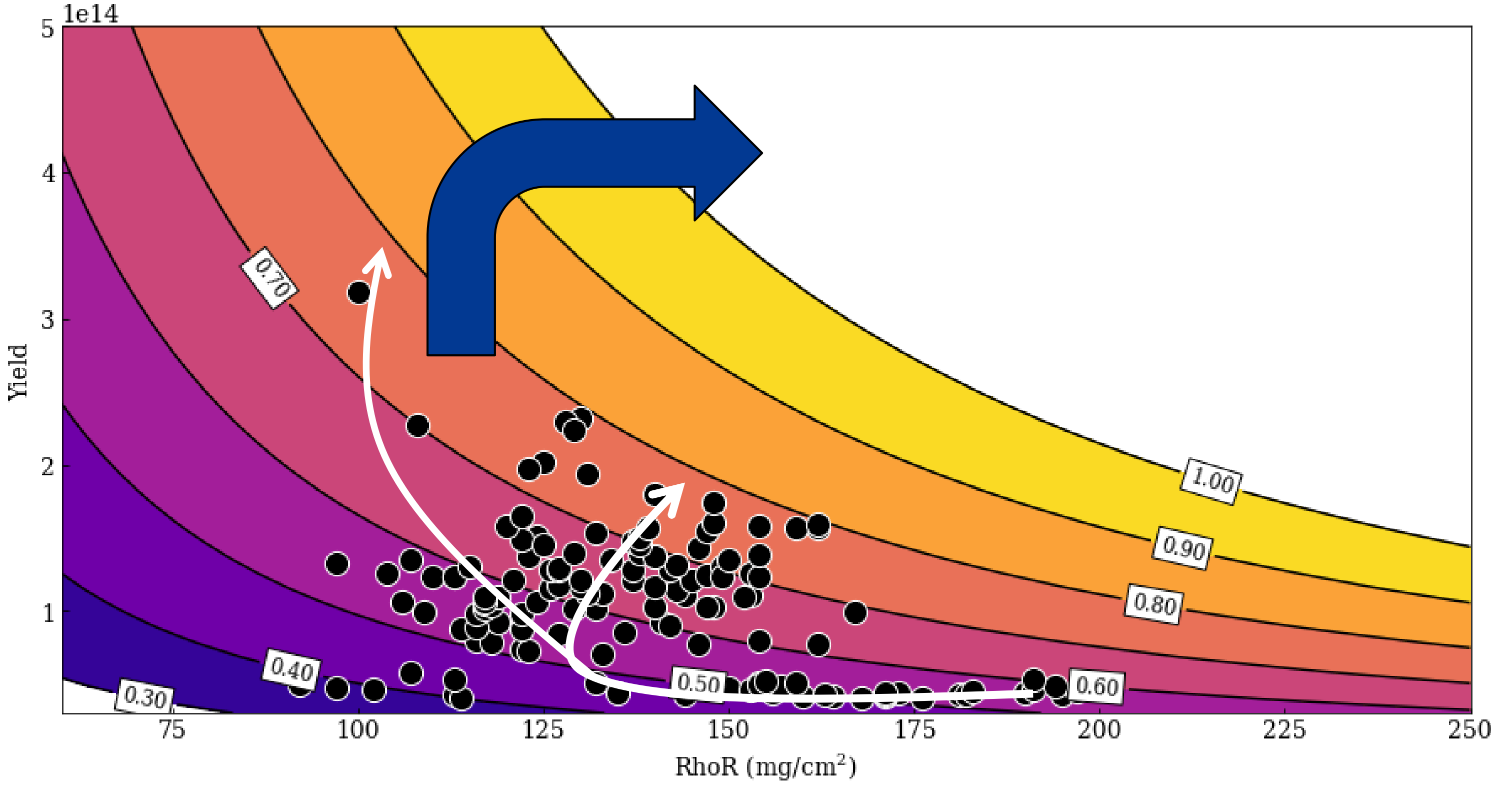
- **Hydro-scaling may be a conservative estimate**
  - **faster scaling seen in experiments***
- **Instability seeds (imprint, stalk, target quality) expected to get better with scale (e.g. 17 um stalk at OMEGA scale vs 2.5 um fill tube at NIF scale)**
- **LPI may become worse**,†**

R. Betti *et al*., Phys. Rev. Lett. 114, 255003 (2015).
A. R. Christopherson *et al*., Phys. Plasmas 25, 012703 (2018);
A. R. Christopherson *et al*., Phys. Plasmas 25, 072704 (2018).
ICF: inertial confinement fusion

* C. A. Thomas *et al*., CO04.00010, this conference.
** A. Solodov *et al*., UO04.00005, this conference.
† M. J. Rosenberg *et al*., UO04.00004, this conference.

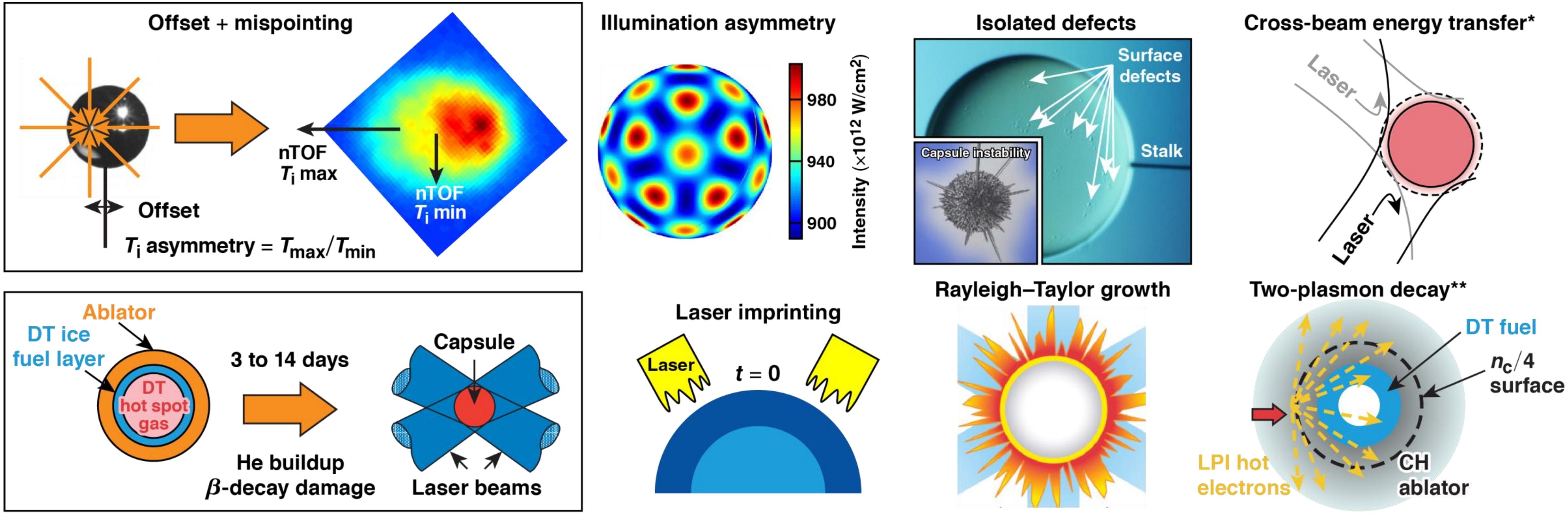
The path to hydro-equivalent ignition most likely requires an increase in both yields and areal densities

Contours of $\chi_{\text{no }\alpha}$ extrapolated to 2 MJ of symmetric drive



Yield Optimization

The factors impacting the performance of direct-drive ICF implosions can be parametrized and quantified using the statistical model

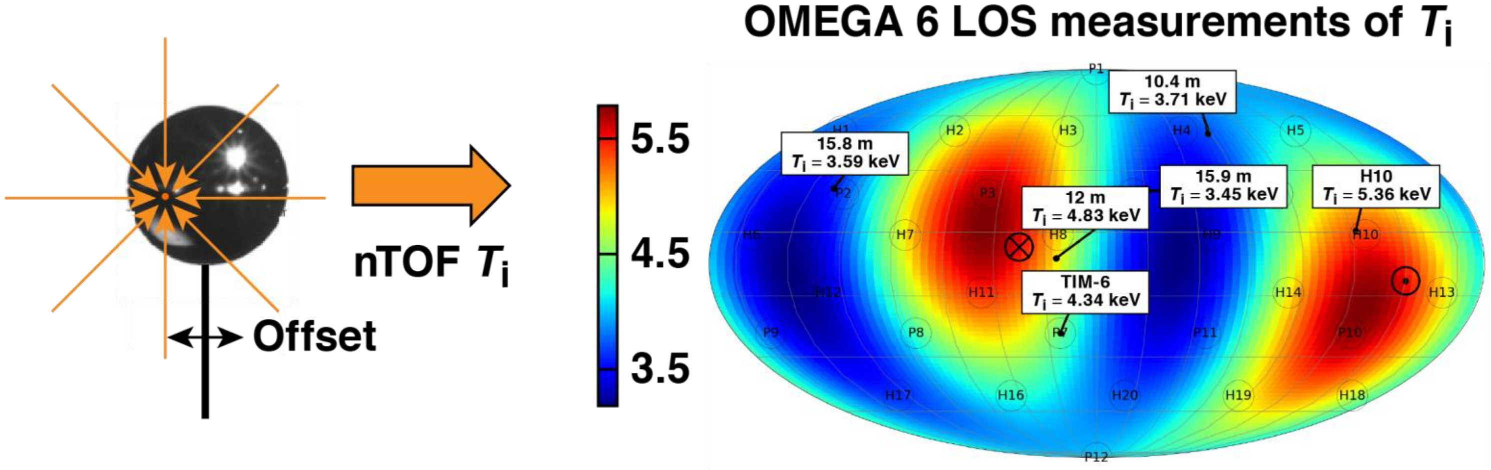


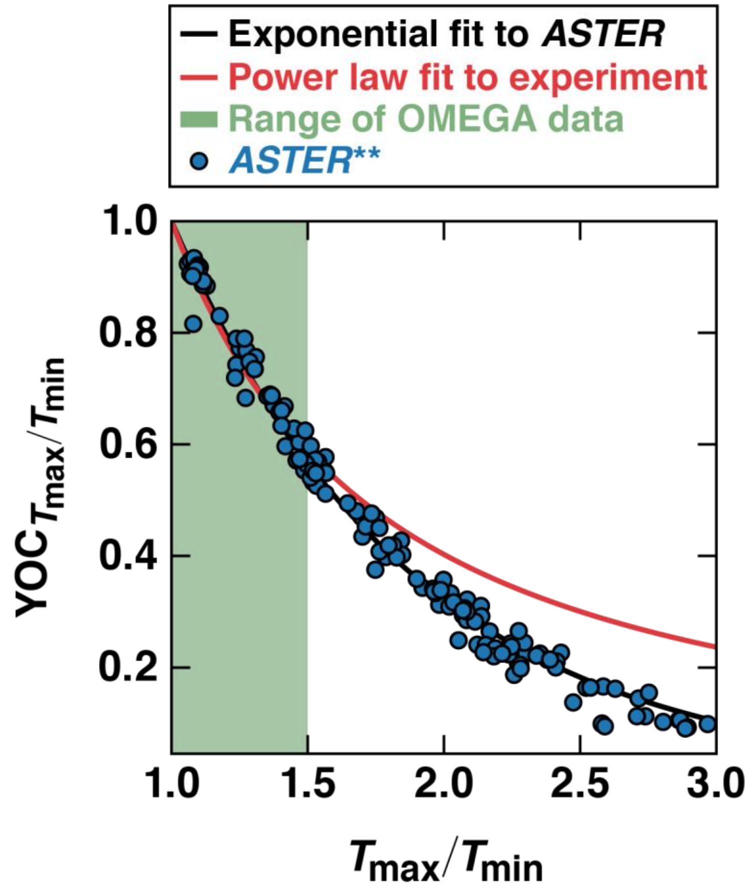
TC15568a

nTOF: neutron time-of-flight
DT: deuterium-tritium
LPI: laser-plasma instabilities

* D. Turnbull, Bull. Am. Phys. Soc. 64, BAPS.2019.DPP.DI3.3 (2019).
** A. A. Solodov *et al*., Bull. Am. Phys. Soc. 65, BO09.00012 (2020).

The effects of the $\ell = 1$ mode from offset and mispointing are assessed through the measured T_i asymmetries





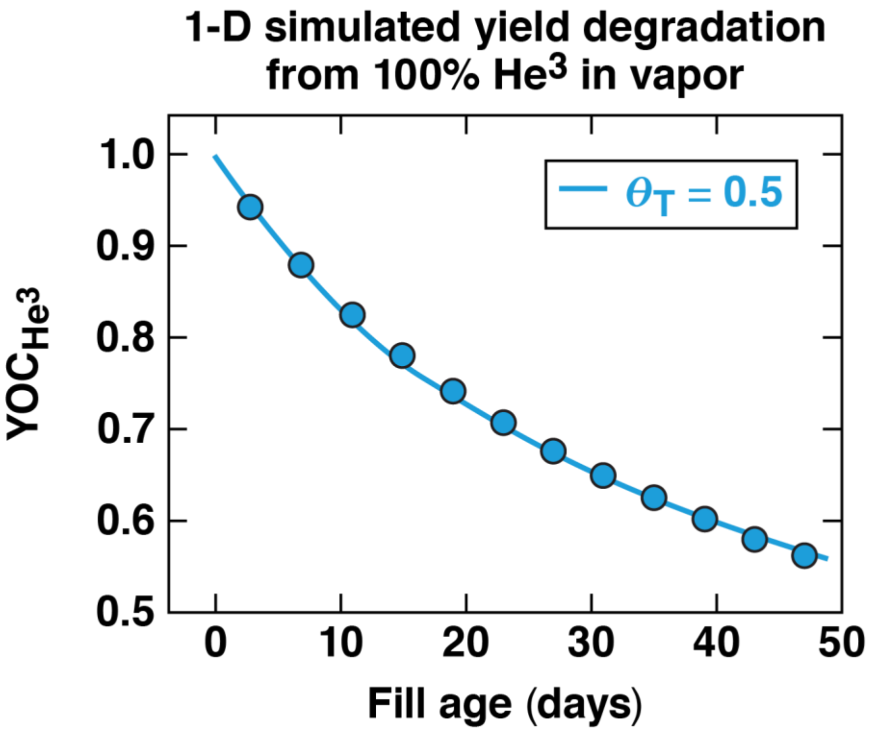
- **In 3-D simulations,* the yield degradation from the $\ell = 1$ mode is a monotonic function of T_{max}/T_{min}**

TC15573a

* V. Gopalaswamy *et al*., "Using Statistical Modeling to Predict and Understand Fusion Experiments," to be published in Physics of Plasmas.
** K. M. Woo *et al*., Phys. Plasmas 27, 062702 (2020).
LOS: line of sight

He^3 produced from tritium decay accumulates in the vapor over time and results in inefficient stagnation

- $\mathrm{YOC}_{\mathrm{He}^3}$ can be calculated from the yield ratio of simulations with and without He^3 buildup
- In simulations, all He^3 is added to DT vapor
- Tritium decay also damages the ablator



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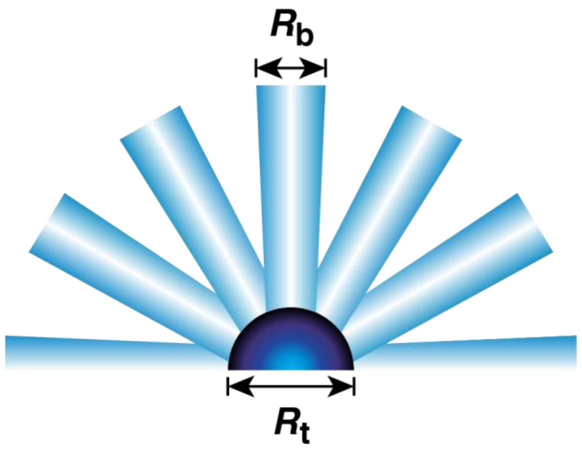
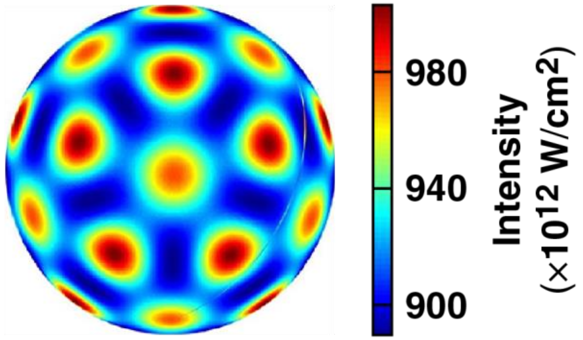
A. Lees *et al.*, Phys. Rev. Lett. 127, 105001 (2021).
YOC: yield over clean

The 3-D simulation code *ASTER* indicates that the yield degradation due to the beam mode is directly related to the illumination nonuniformity and stability of the target





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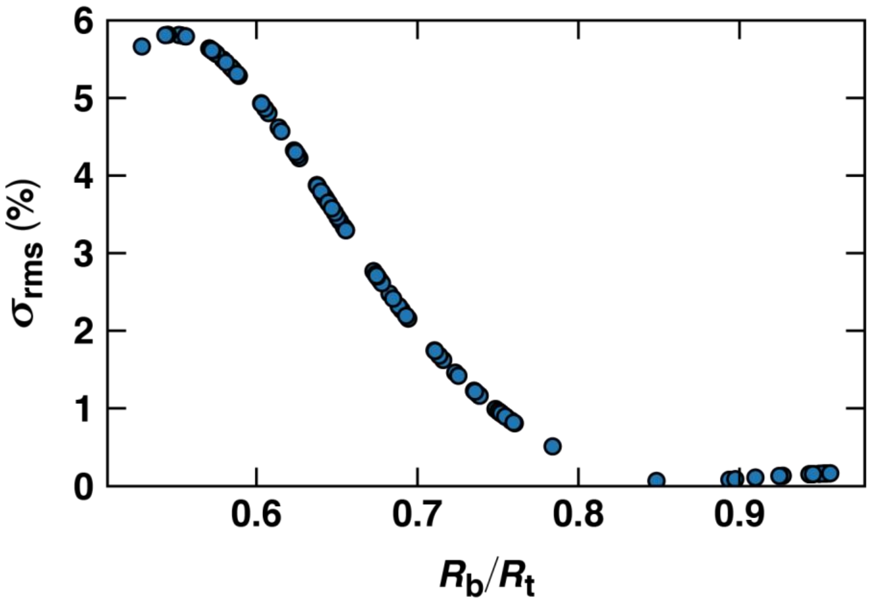
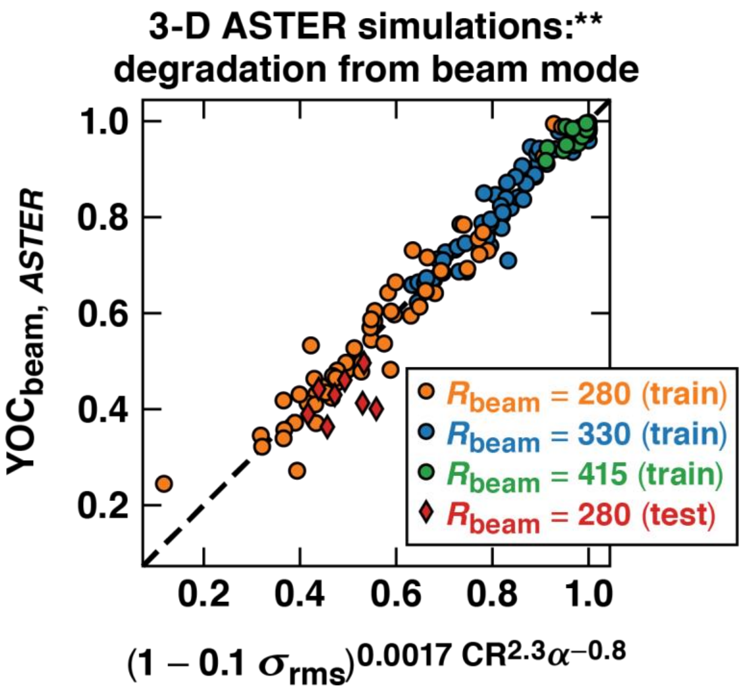
Hard sphere illumination nonuniformity is closely related to R_b/R_t





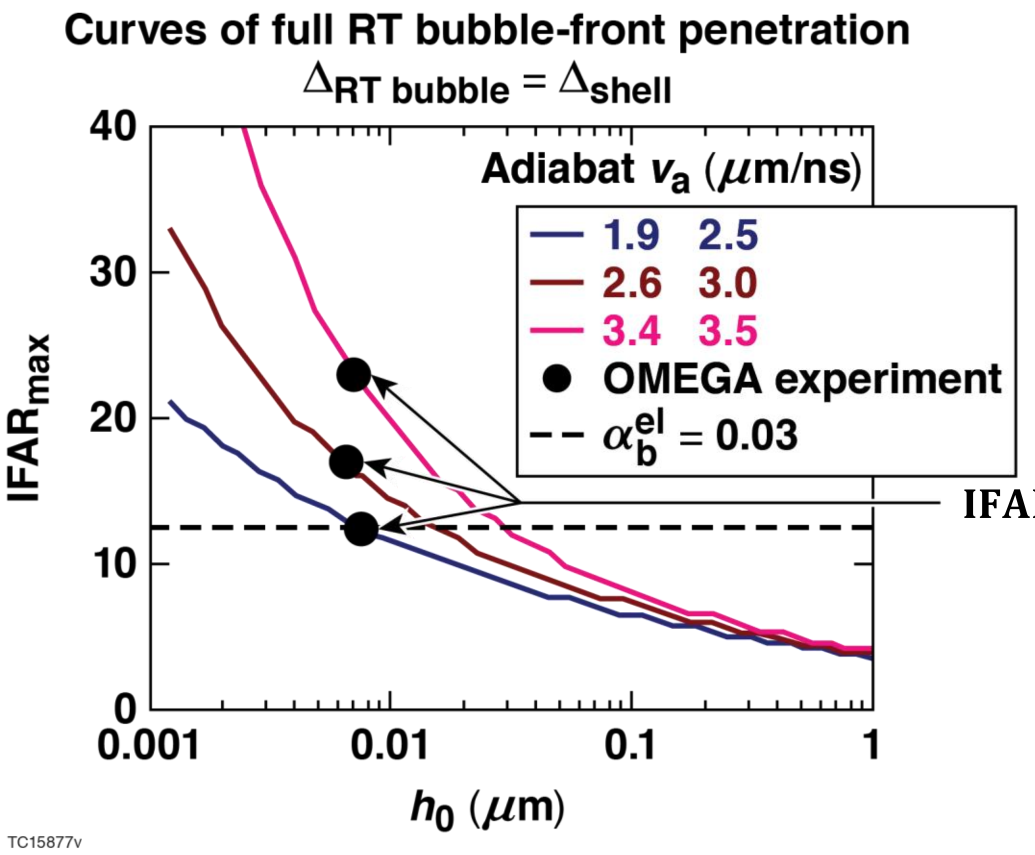
$$YOC_{beam,\ ASTER} = (1 - 0.1\ \sigma_{rms})^{0.0017 CR^{2.3}\alpha^{-0.8}}$$

rms: root mean square

* A. Lees *et al*., Phys. Rev. Lett. 127, 105001 (2021).

** V. Gopalaswamy *et al*., "Using Statistical Modeling to Predict and Understand Fusion Experiments", accepted in Physics of Plasmas.

A critical parameter based on the IFAR and adiabat determines when short wavelength RT penetrates the shell



$$\mathrm{IFAR}_{2/3} \sim 20\left(\frac{\alpha_F}{3}\right)^{1.1} *$$

$$\boxed{\mathrm{YOC}_{sw} \sim \left(\frac{\alpha_F^{\delta}}{\mathrm{IFAR}}\right)^{\sigma}}$$

σ changes when
$\Delta_{\text{RT-bubble}} \geq \Delta_{\text{shell}}$

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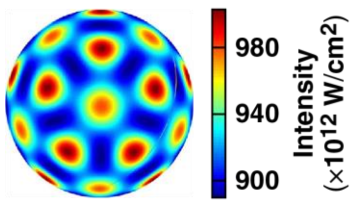
* V. N. Goncharov *et al*., Phys. Plasmas 21, 056315 (2014).
H. Zhang *et al*., Phys. Plasmas 27, 122701 (2020).
RT: Rayleigh–Taylor
IFAR: in-flight aspect ratio

The overall dependence of the YOC is built using physics-based parameters from *LILAC*, representing mostly known degradation phenomena, although some dependencies are yet to be explained

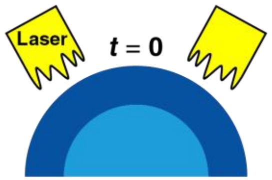
CBET/1-D physics? | Beam mode | Short wavelengths | $\ell = 1$ | Tritium decay | See C. Thomas talk*

$$\mathrm{YOC} \sim \left(\frac{R_\mathrm{b}}{R_\mathrm{t}}\right)^{b_1} e^{-(b_2+b_3\alpha+b_4\mathrm{CR})\sigma_\mathrm{rms}^{b_5}} \left(\frac{\alpha_\mathrm{F}^{b_6}}{\mathrm{IFAR}}\right)^{b_7,b_8} \max\left[\left(\frac{T_\mathrm{max}}{b_9 T_\mathrm{min}}\right), 1\right]^{b_{10}} \mathrm{YOC}_{\mathrm{He}^3}^{b_{11}} \mathrm{YOC}_\mathrm{res}$$

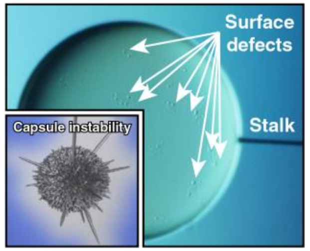
Beam mode



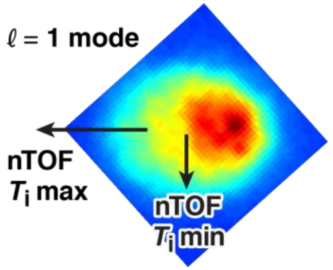
Laser imprinting



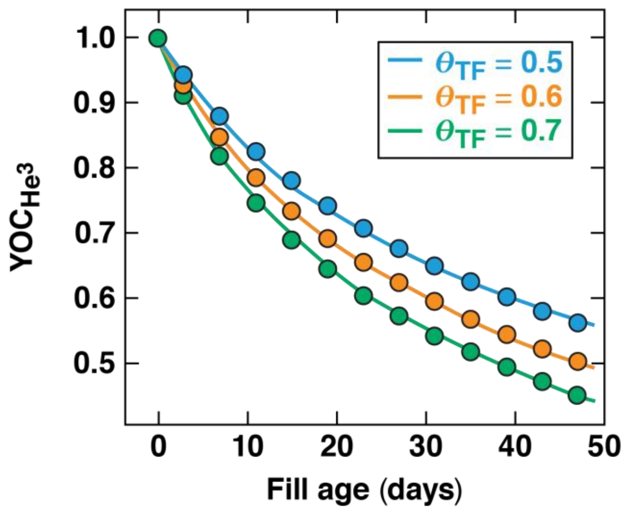
Isolated defects



$\ell = 1$ mode



1-D simulated yield degradation from 100% He^3 in vapor



Two-dimensional *DRACO* can simulate imprint, offset, beam mode, etc. and is in closer agreement with experiments than *LILAC***

Multi-dimensional simulations will be used to form the statistical model in the future

V. Gopalaswamy *et al*., Nature 565, 581 (2019).
*C. A. Thomas *et al*., CO04.00010, this conference.
** D. M. Cao *et al*., TO07.00001, this conference
CBET: cross-beam energy transfer

TC15568b

Predictive statistical models of the neutron yield are extremely accurate and speed up validation of yield-increasing designs

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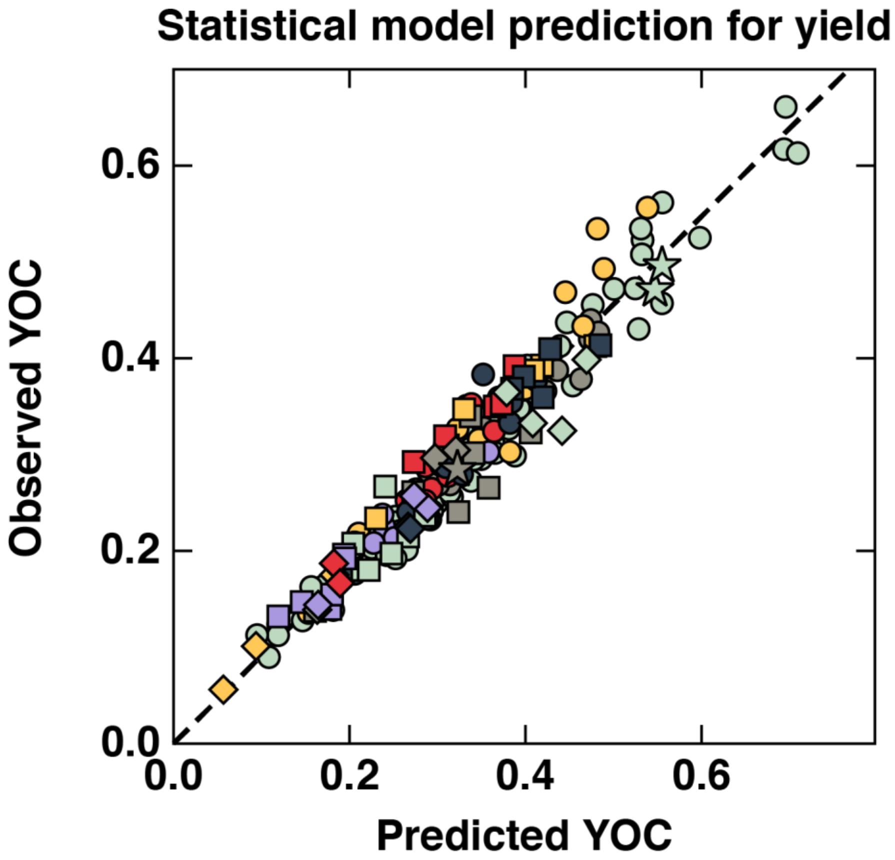
Shot-to-shot variations in initial conditions, and $\ell = 1$ need to be factored out



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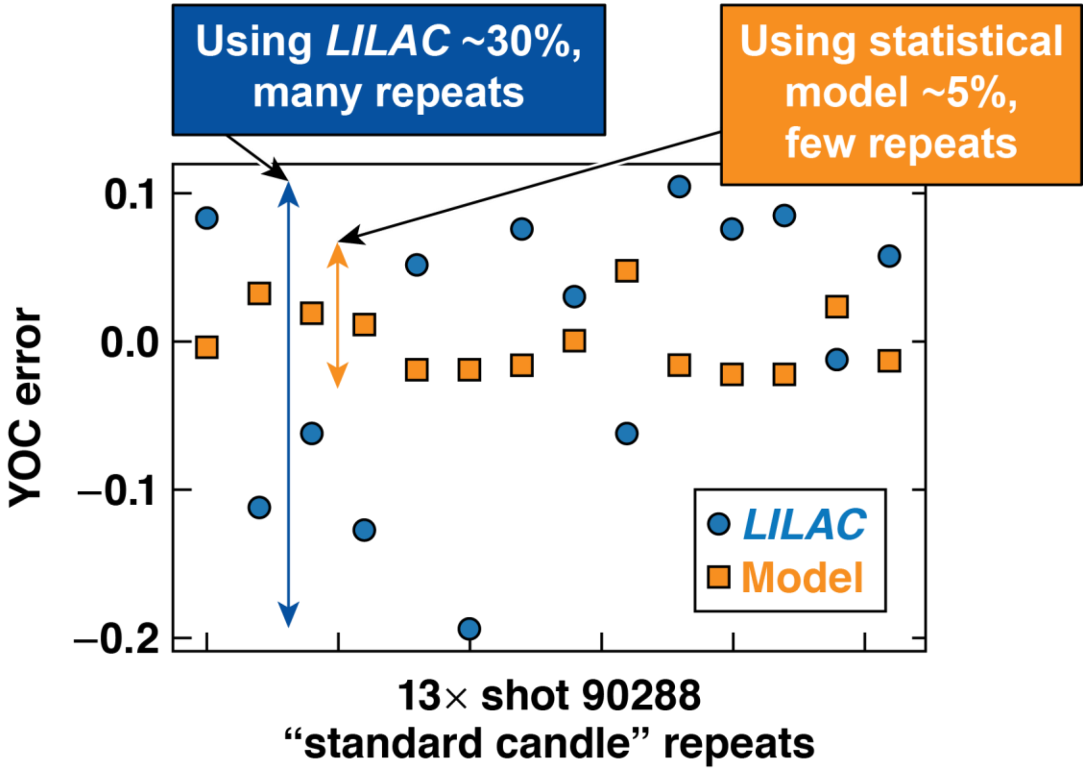
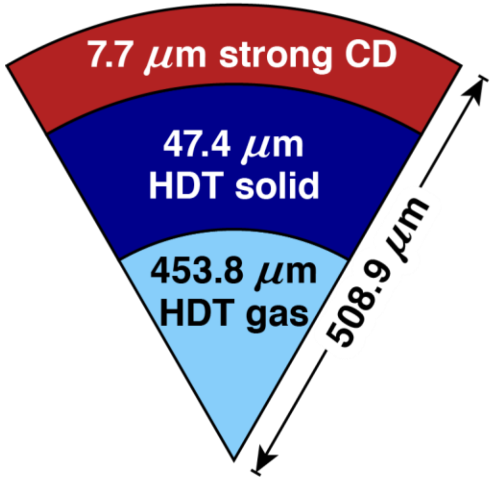
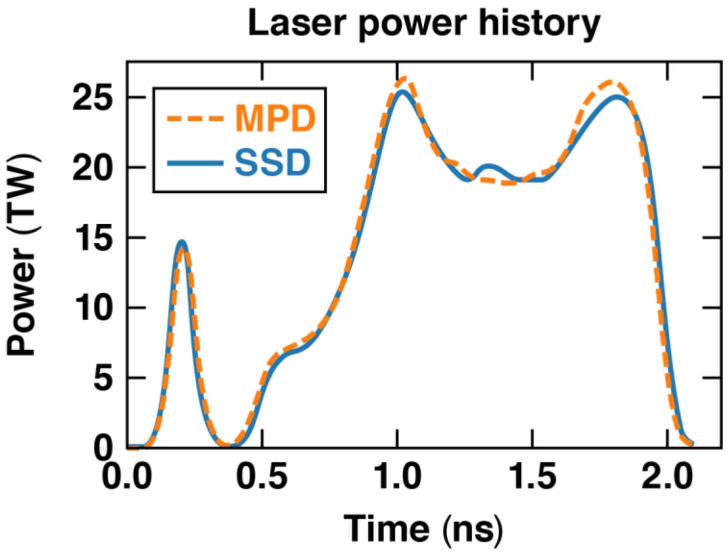
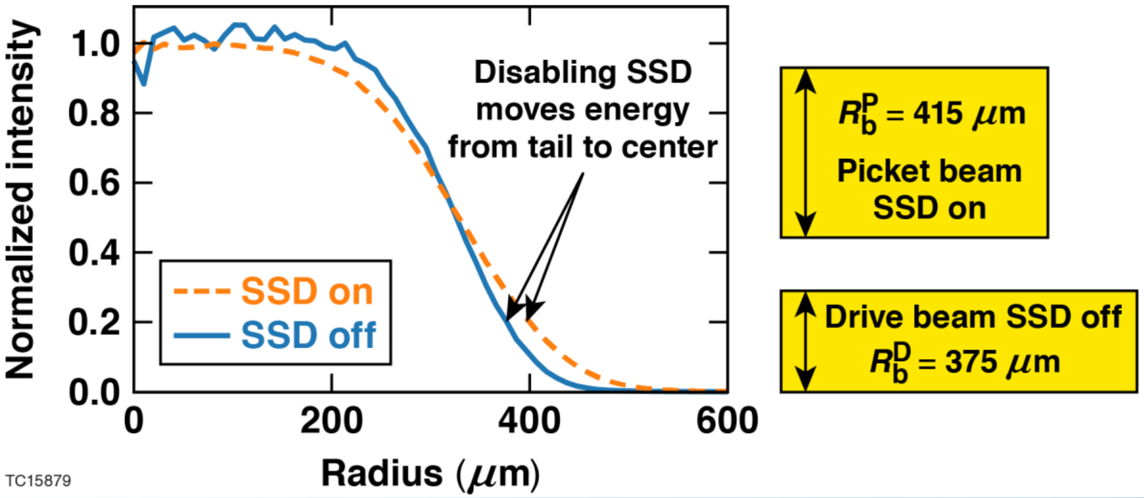


V. Gopalaswamy *et al*., Nature 565, 581 (2019).
A. Lees *et al*., Phys. Rev. Lett. 127, 105001 (2021).

Initial A/B tests on OMEGA are promising and indicate that the best-performing implosions could have their yields increased by at least ~10% to 20%



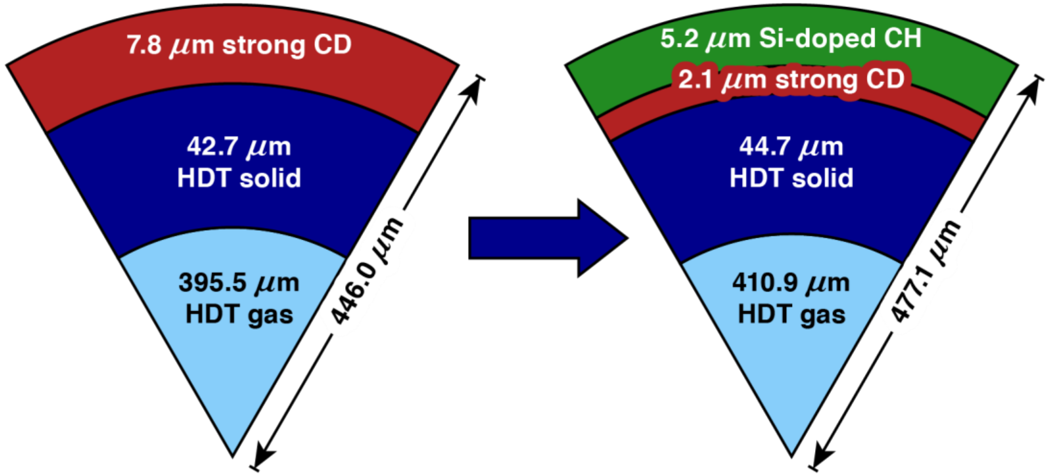


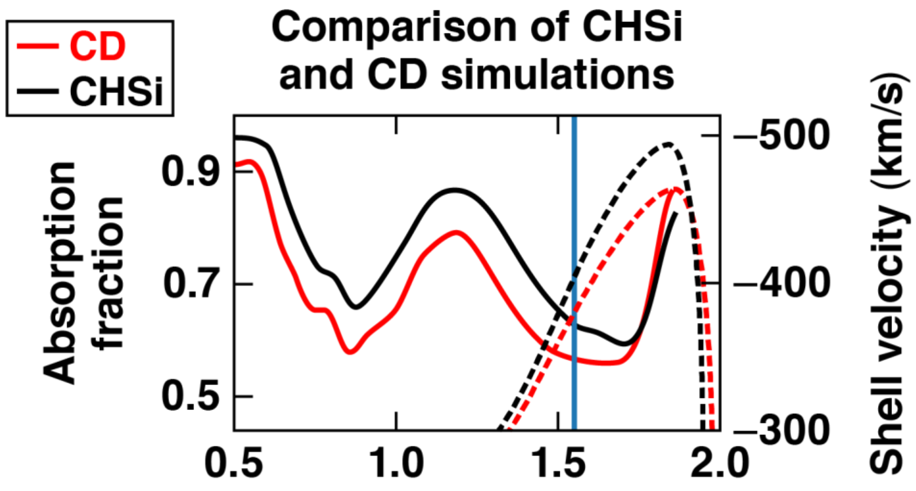


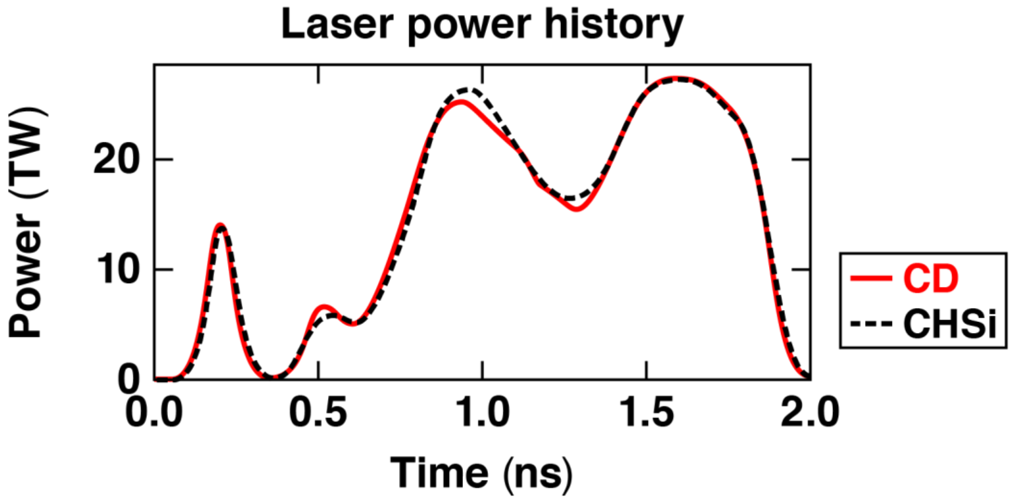
	Shot 100535 (SSD)	Shot 100982 (MPD)
Yield (correcting for $\ell = 1$ and He^3)	1.68×10^{14}	1.90×10^{14} (+13%) *LILAC* (+29%)
LILAC implosion velocity (km/s)	474	510
Bang time, ps (experiment)		–70±25 ps

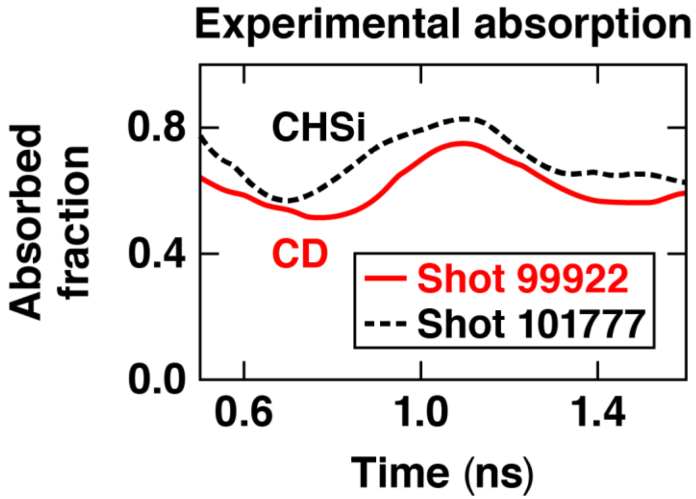
Si-doped

Mid-*Z* doped ablators achieve higher yields by increasing laser energy absorption









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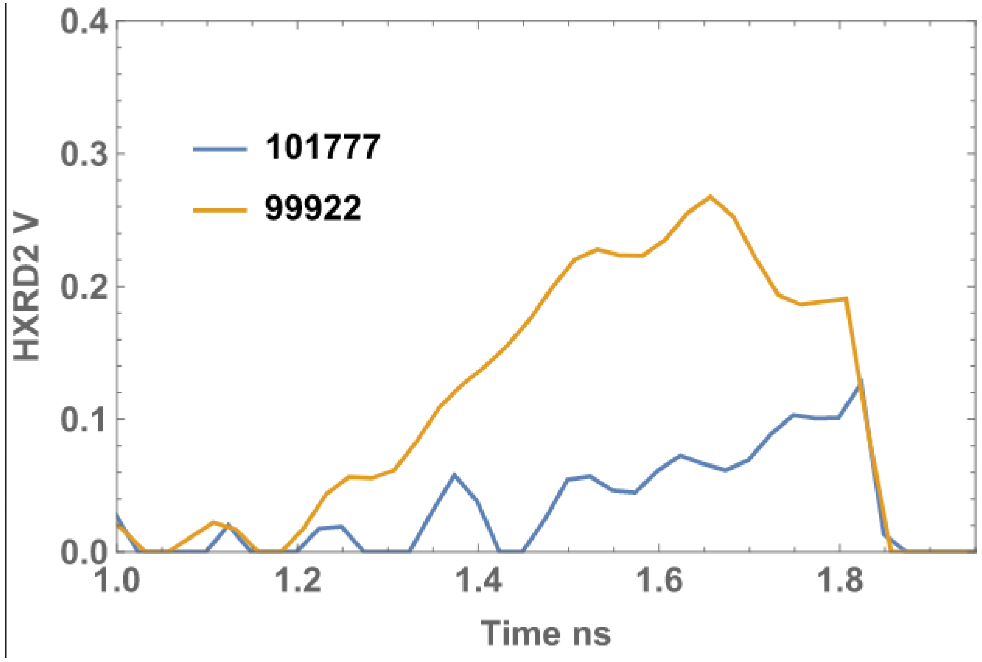
Si-doped

Initial A/B tests show Si-doped shells lead to higher yields and mitigate hot-electron preheat

Hard x-ray signal comparison* between CD and CHSi



	CHSi (Shots 102154/ 102162/10177)	CD (Shot 99922)
Experimental yield	2.0 to 2.25 $\times$ 10^{14}	1.6 $\times$ 10^{14}
HXRD (pC)	53$\pm$16	195$\pm$24
Absorption fraction	73% (*LILAC*) 69$\pm$5% (experiment)	66% (*LILAC*) 59$\pm$5% (experiment)

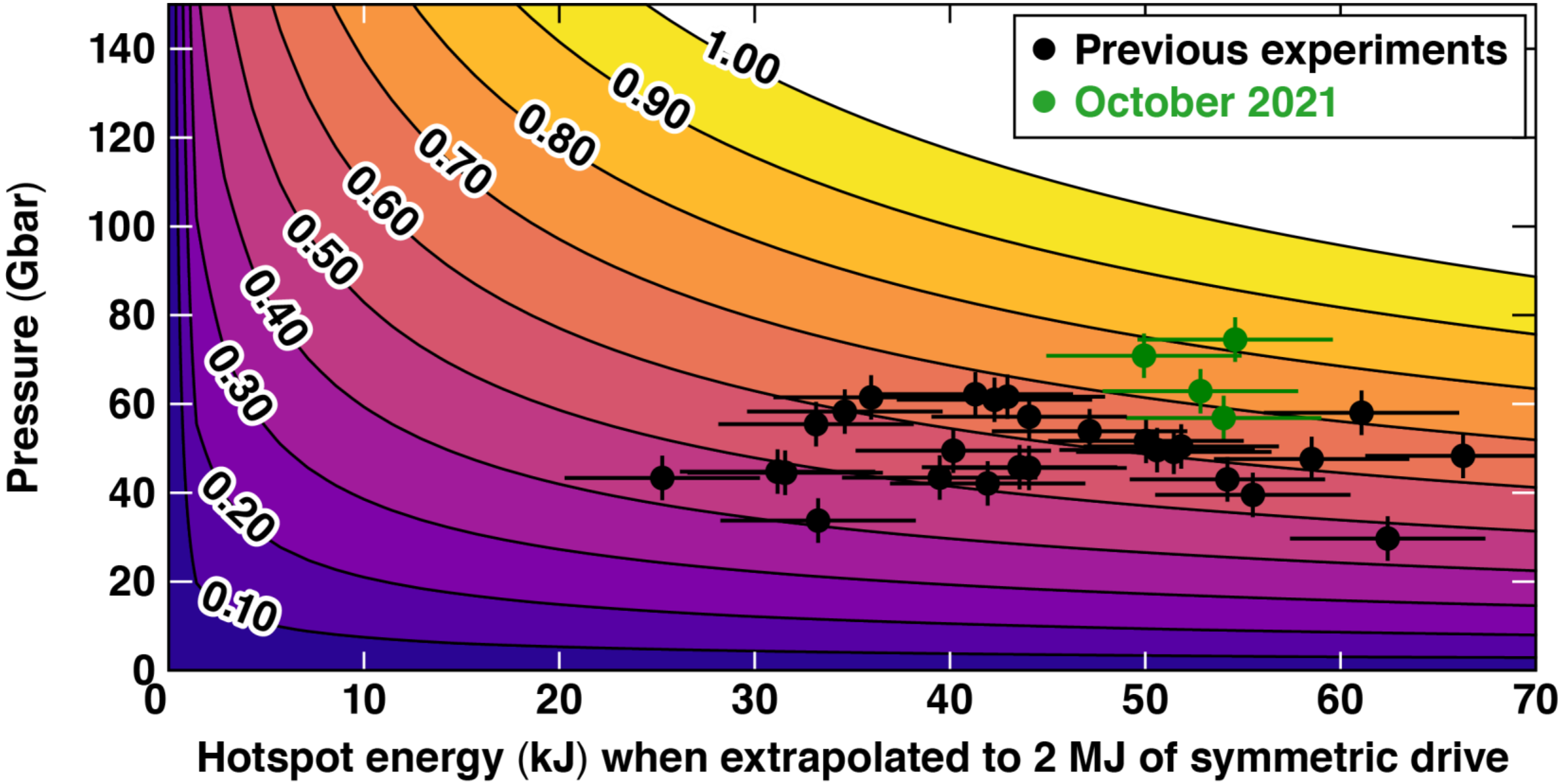
Highest yields to date achieved with Si-doped targets

* D. P. Patel *et al.*, TO07.00014, this conference.
** D. Patel, C. Stoeckl, and D. Edgell, Laboratory for Laser Energetics, private communication (2021).
HXRD: hard x-ray detector

Si-doped

The performance metric of the Si-doped ablators show a marked increase compared to the plastic ablators

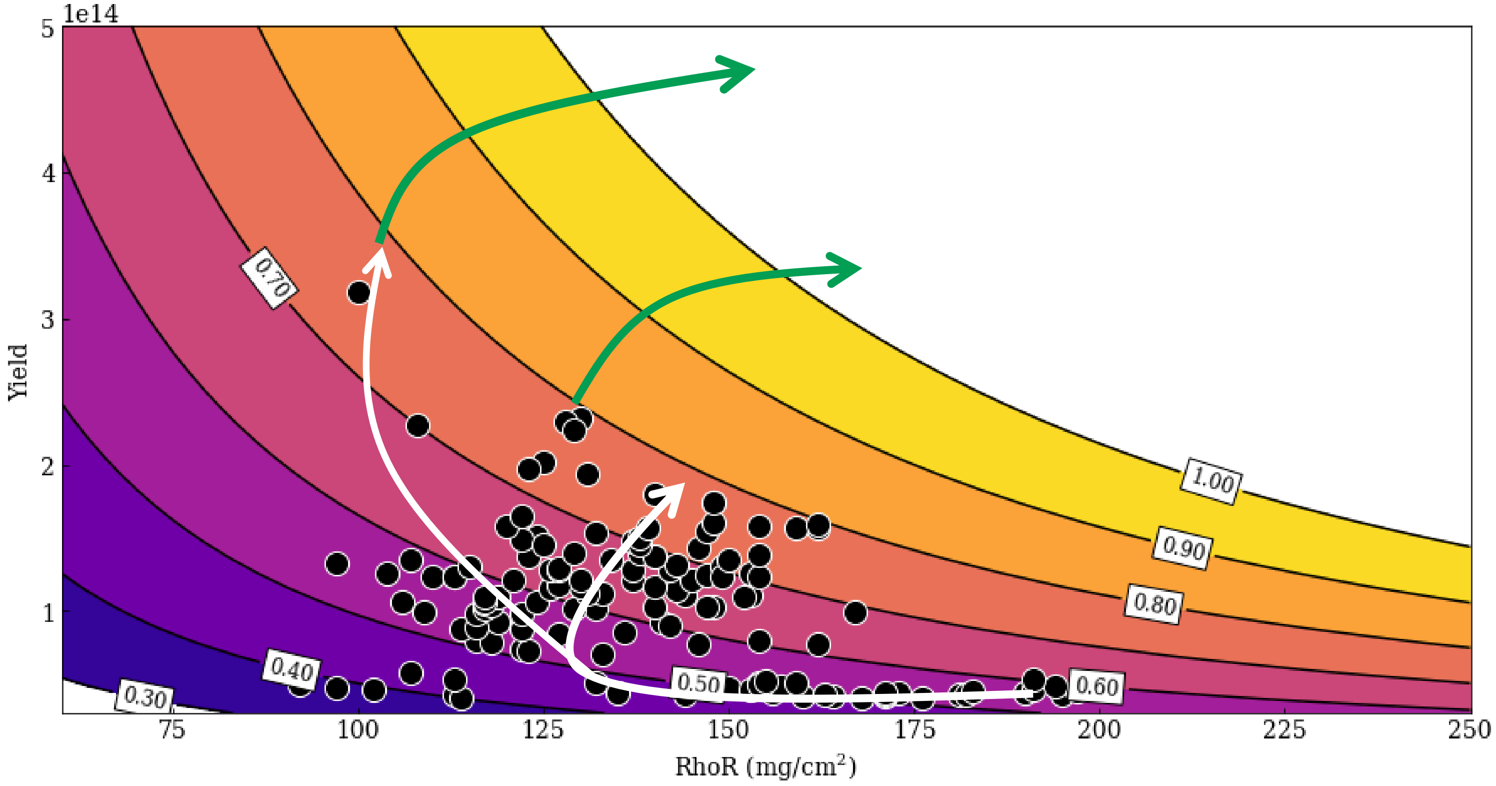
Contours of $\frac{P\tau}{\langle P\tau \rangle_{\text{ign}}}$



TC15876b

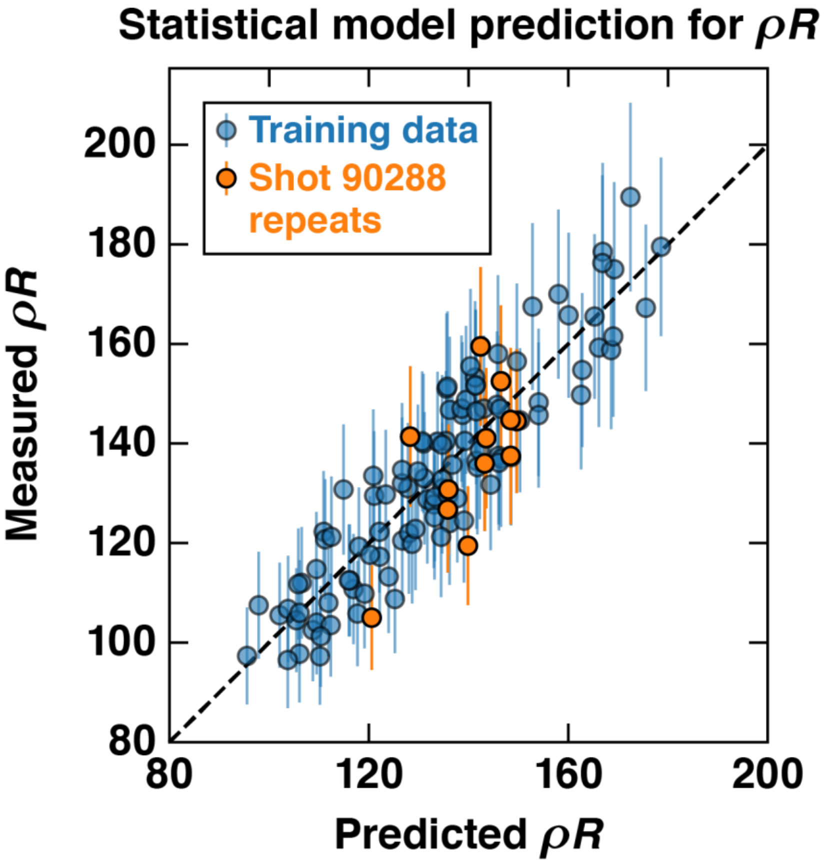
Once the yields have been increased to 3-4 × 10^{14}, dedicated experiments will focus on increasing ρR

Contours of $\chi_{\text{no}\,\alpha}$ extrapolated to 2 MJ of symmetric drive



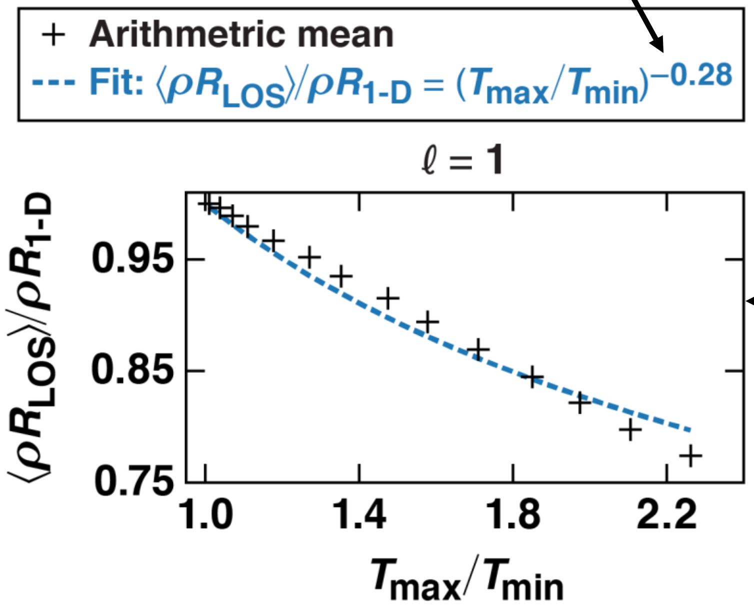
Achieving hydro-equivalent ignition will require further increases in yields and areal densities

Statistical predictions for ρR are not yet sufficiently accurate to quickly validate design due to anisotropy and inaccuracy of the measurement, and sensitivity to shock timing



TC15883

$$\frac{\rho R_{\mathrm{exp}}}{\rho R_{\mathrm{sim}}} \sim \mathrm{CR}^{-0.6}\left(\frac{T_{\mathrm{max}}}{T_{\mathrm{min}}}\right)^{-0.3}\left(\frac{\alpha_{\mathrm{F}}^{1.3}}{\mathrm{IFAR}}\right)^{0.4,0.2}\left(\frac{R_{\mathrm{b}}}{R_{\mathrm{t}}}\right)^{0.2}$$



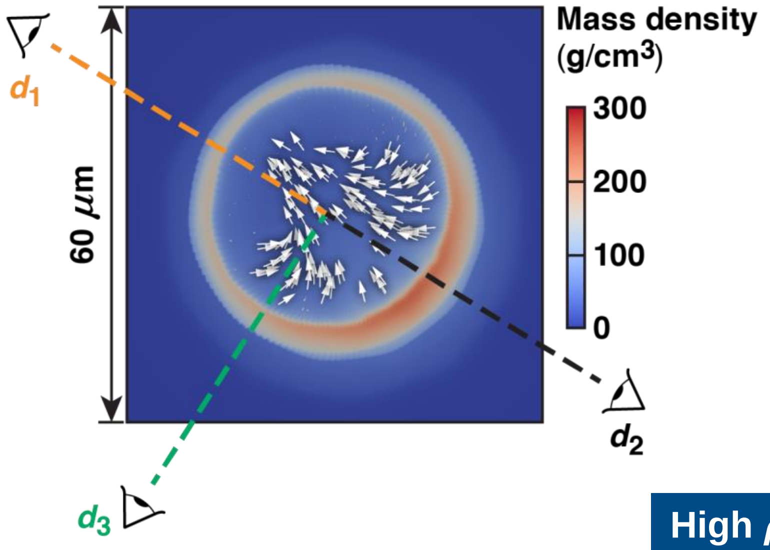
Dependence of average ρR on T_{i} ratio from 3-D simulations

K. M. Woo and R. Betti, Phys. Plasmas 28, 05450 (2021).

With limited lines of sight, the measured ρR is not generally equal to $\langle \rho R \rangle$*, which is a critical parameter for χ when the target is perturbed

Density contours in *ASTER* simulation with large $\ell = 1$ perturbation

Low ρR

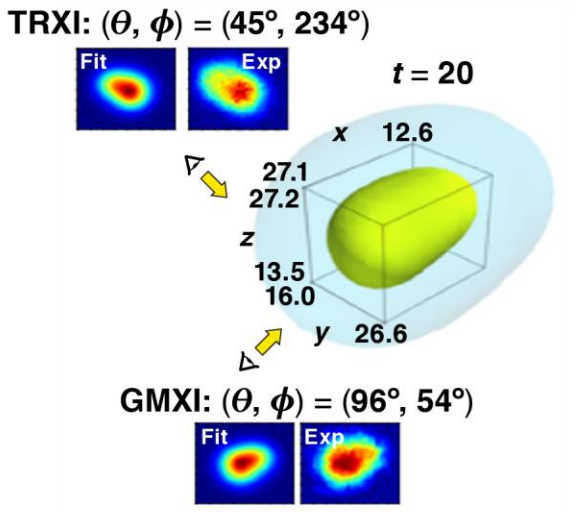


High ρR

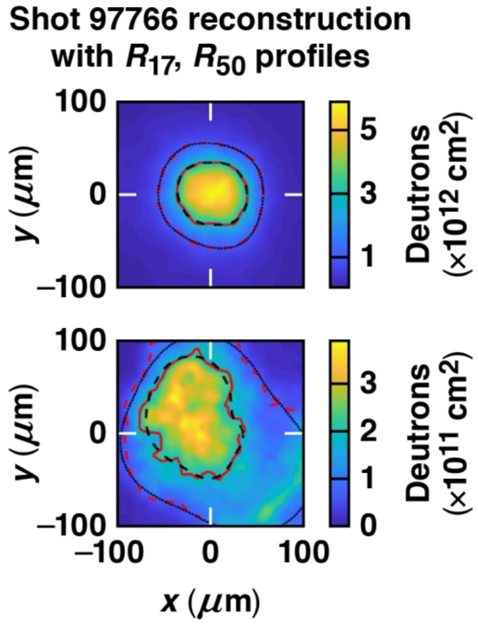
Medium ρR

Need a method to infer the 4π averaged areal density $\langle \rho R \rangle$ from limited measurements

3-D reconstruction can help reconcile measurements**



KODI† hotspot and cold shell reconstruction

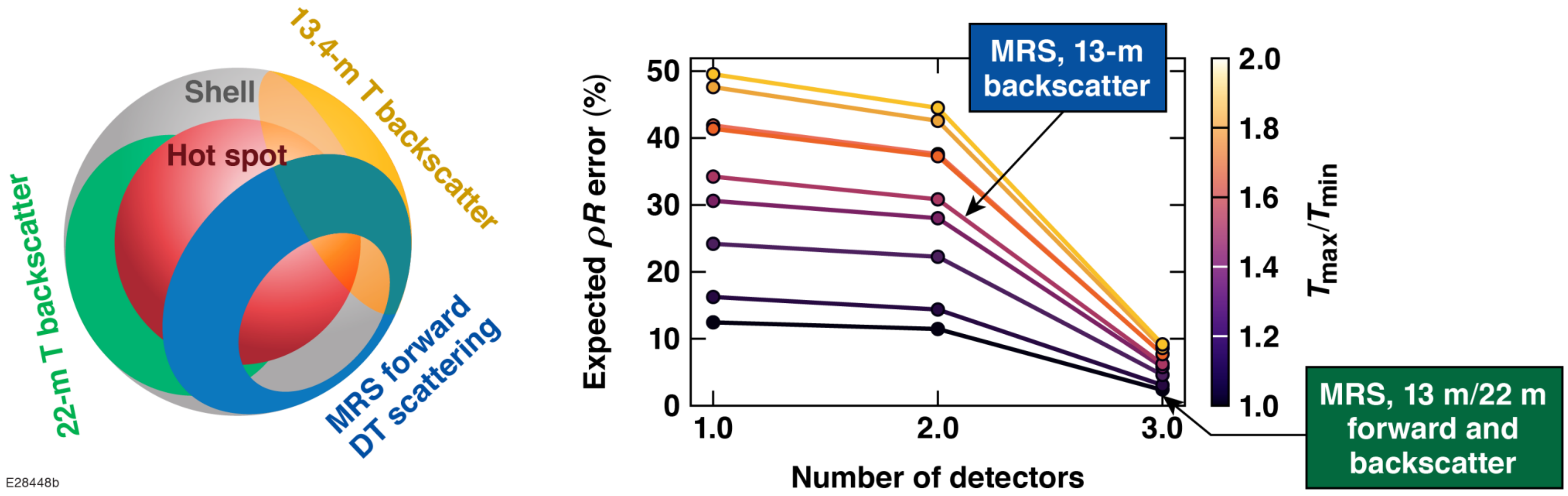


GMXI: gated monochromatic x-ray imager
TRXI: time-resolved x-ray imager
KODI: knock-on deuteron imager

* J. P. Knauer *et al*., NO04.00009, this conference
** R. C. Shah *et al*., CO04.00012, this conference.
† H. Rinderknecht *et al*., GO05.00012, this conference.

The error on $\langle \rho R \rangle$ from limited lines of sight is bounded and sufficient detector coverage can make it negligible

Expected % ρR error for $\ell = 1$



nTOF forward-scattering measurements for OMEGA are currently under development, and the measurement analysis on each LOS is being refined to reduce systematic error.

MRS: magnetic recoil spectrometer

Flow-motivated offsets can mitigate $\ell = 1$ modes, and simulations indicate that $\langle \rho R \rangle$ can be reconstructed from individual measurements

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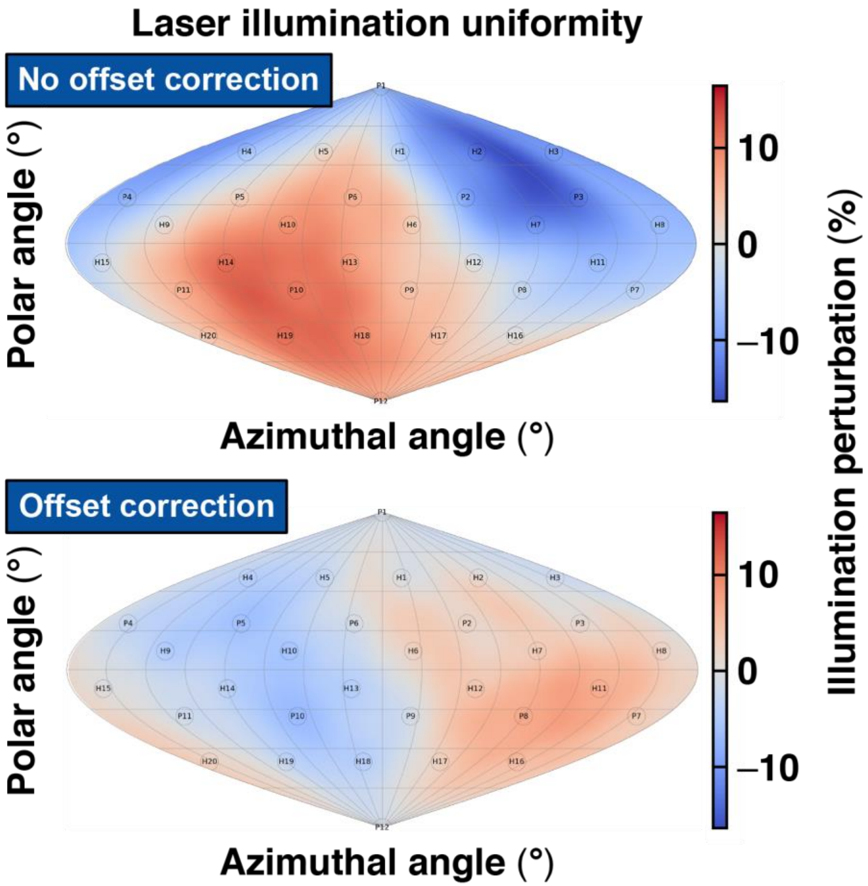
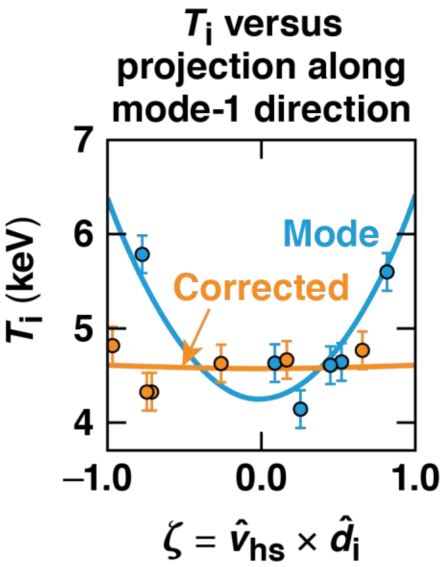
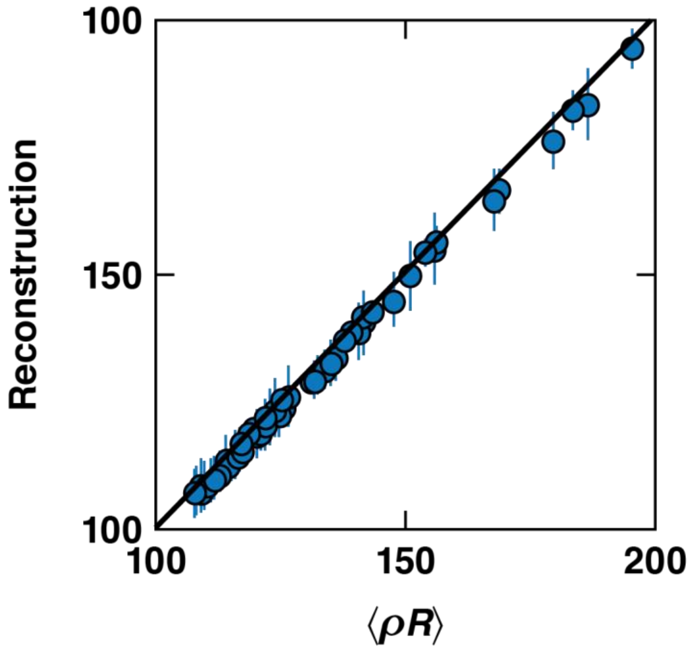
$\ell = 1$ is corrected with imposed offsets*





$\ell = 1$ asymmetry can be corrected if flow and T_{max}/T_{min} is known



E29335a

*O. M. Mannion *et al.*, Phys. Plasmas 28, 042701 (2021).

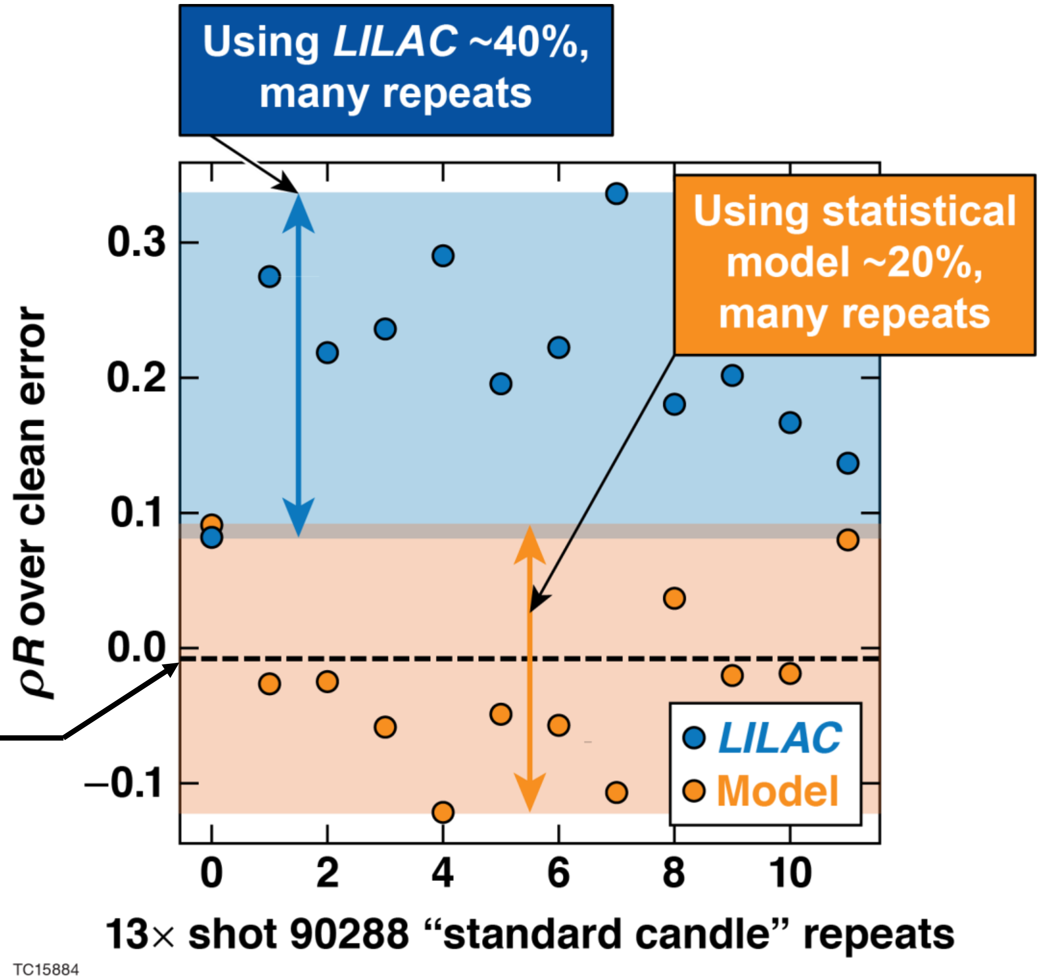
Accurate measurement of the $\langle \rho R \rangle$ can more than double the effective shot rate when the goal is an increase in $\langle \rho R \rangle$

Over multiple repeats, average of measurements = $\langle \rho R \rangle$

Statistical model predicts $\langle \rho R \rangle$
not an individual measurement

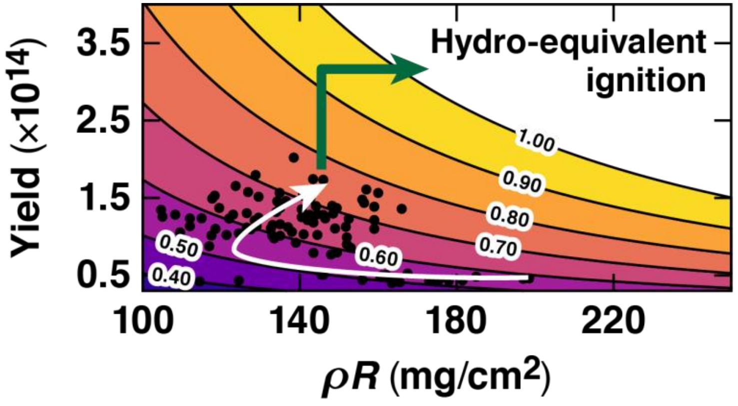
Need many repeats to validate $\langle \rho R \rangle$ increase ~ 20%

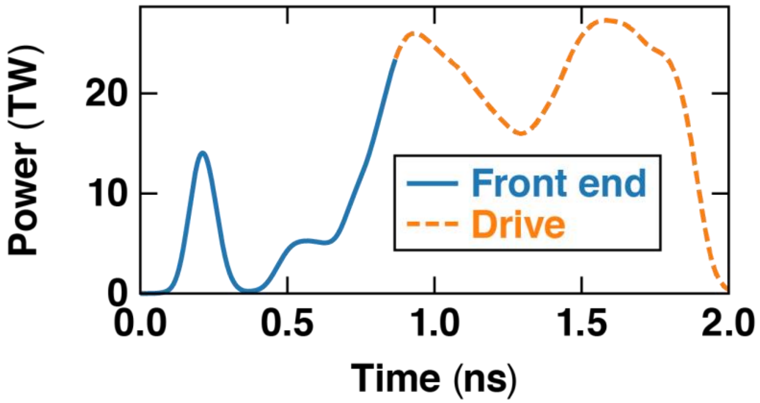
Accurate measurement of $\langle \rho R \rangle$ can reduce the number of repeats needed to verify a design



Careful tuning of the pulse shape front end and target quality improvements can lead to $\langle \rho R \rangle$ improvements and hydrodynamically-equivalent ignition

Contours of $\chi_{no\ \alpha}$ extrapolated to 2 MJ of symmetric drive

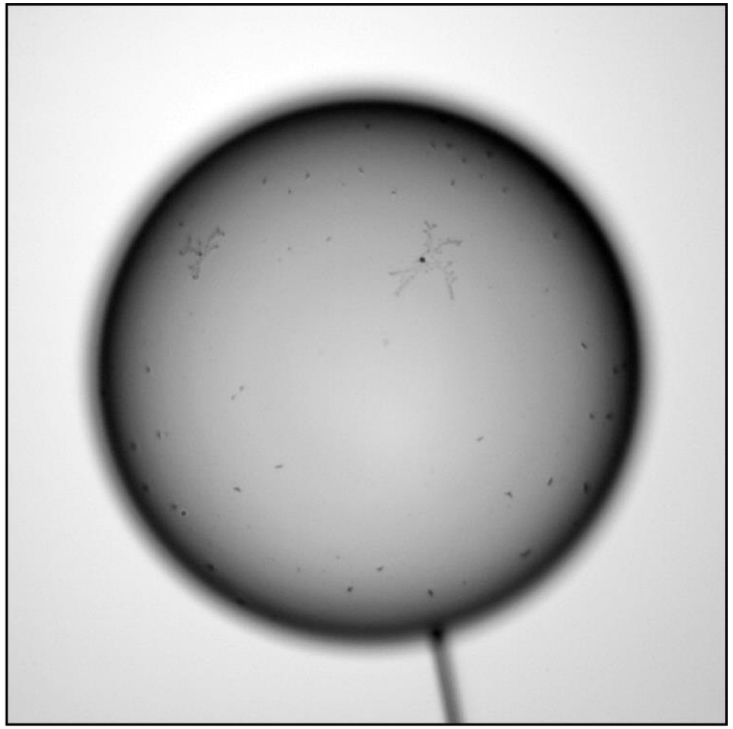




TC15885

At yields ~3 $\times$ 10^{14}, the drive/target specs will be fixed and focus will be on optimizing the adiabat via the front end of the laser to increase ρR.

Target defects drive jets that can increase vapor density and can severely degrade ρR*



* I. V. Igumenshchev *et al*., Phys. Plasmas 20, 082703 (2013).

Summary

Record yields and extrapolated Lawson parameters have been achieved on OMEGA

- Recent implosions have demonstrated yields of 2.3e14, giving $\chi = 0.8$ and 1 MJ of fusion yield at 2 MJ of symmetric drive with over 80 Gbar of pressure
- The path toward hydro-equivalent ignition is to maximize fusion yields at constant ρR, and then increase ρR
- The statistical model allows for rapid validation of design for increased fusion yields by adjusting for shot-to-shot variations
- The use of the multipulse driver (MPD) and mid-*Z*-doped ablators has shown promise in increasing yields through increasing coupling
- Increasing ρR is challenging due to the inherently asymmetric nature of the measurement
- Once the yield is sufficiently high, the ρR will be increased by optimizing shocks