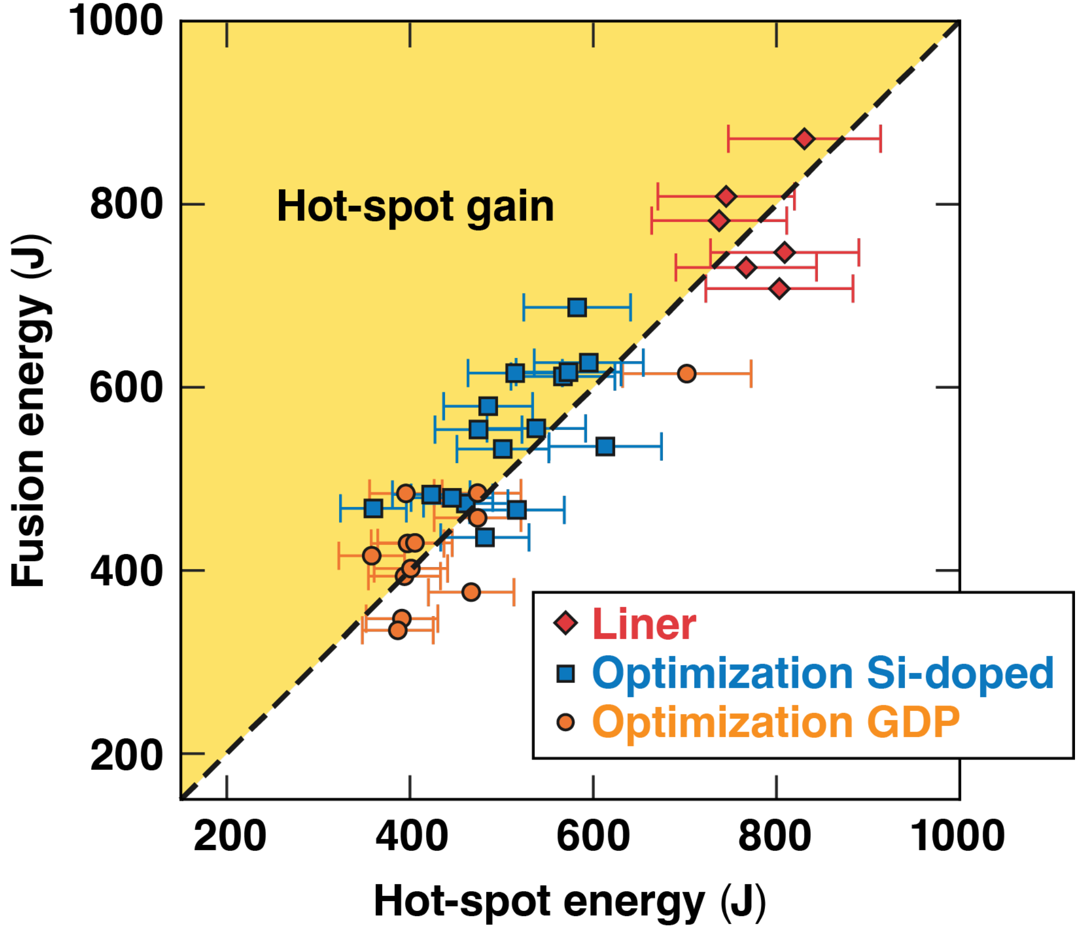
Achieving Highest Fusion Yields in OMEGA Direct-Drive ICF Through Improved Energy Coupling



TC16273

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64th Annual Meeting of the
American Physical Society
Division of Plasma Physics
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Summary

Recent OMEGA implosions have achieved fuel gains >1 and record fusion yields above 3×10^{14}

- Highest yields on OMEGA (3.1×10^{14}) achieved using low-convergence, high-velocity (~600 km/s) DT liners
- 1st demonstration of fusion energy exceeding hot-spot energy in SDD* using both high CR** targets and liners
- Silicon doping and multipulse-driver (MPD) show enhanced laser-to-target coupling
- Pressures near 80 Gbar reached with highest hydroscaled χ (0.83) at 2 MJ of laser energy, corresponding to the burning plasma regime

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* SDD: symmetric directdrive

** CR: convergence ratio = R_0 / R_{hs}

Collaborators

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General Atomics

Motivation

Optimization campaign

- Goal to achieve hydro-equivalent ignition ($\chi = 1$) when scaled to 2 MJ of laser energy*

Thin-ice DT liner campaign

- Goal to produce the highest possible yields with the most stable implosions
- Possible neutron source on the NIF
- Lower convergence ratios and lower χ but higher yields

Hydro-scaling assumes the same hot-spot pressure at all scales and volume ~ E_{laser}.

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* Betti, R., *et al*. *Physical review letters* 114.25 (2015): 255003.

Outline

- Fusion performance metrics
- Statistical mapping model
- Target and laser pulse modifications and recent achievements

The performance of direct-drive OMEGA implosions is assessed through measurements of the neutron yield and areal density to infer the Lawson parameter

- **Lawson parameter for ICF**[1–5]

Measured with nuclear diagnostics

$$\chi_{3D} = \frac{nT\tau}{\left[nT\tau\right]_{ign}} \approx \left\langle \rho R_{g/cm^2} \right\rangle_{3D}^{0.61} \left(\frac{0.12 Yield_{16}}{M_{DTstag}^{mg}} \right)^{0.34}$$

- **The Lawson parameter is hydroscaled**

$$\chi \sim P\tau \sim \tau \sim R \sim E_L^{1/3}$$

Hydroequivalent ignition: χ = 1 at ≈ 2 MJ

- **Scaled ignition**

For ignition

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

About 4.2 × for 2 MJ

[1] A. Christopherson et al, Phys. Plasmas 27, (2020)
[2] J. D. Lindl et al. Phys. Plasmas 25, 122704 (2018)
[3] R. Betti et al, Phys. Rev. Lett. 114, 255003 (2015)
[4] B.K. Spears et al, Phys. Plasmas 19, 056316 (2012)
[5] O. Hurricane et al, Phys. Plasmas 28, 022702 (2021)

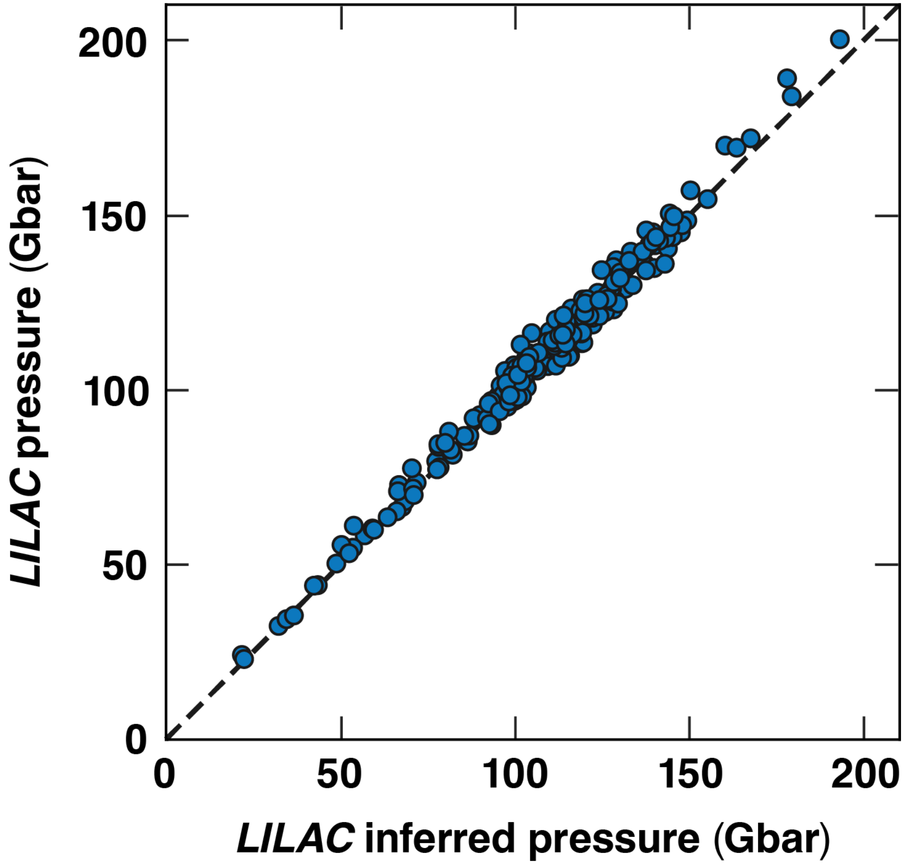
Other performance metrics: hot-spot pressures and energies can be inferred using measurements from neutron and x-ray diagnostics

- Generate constraints on P_{hs} and E_{hs} using

$$Y = f_D f_T \int dt \int_0^{R_{hs}} d^3r \frac{P_i^2}{T_i^2} \langle \sigma v \rangle$$

- $T_i \neq T_e$.
- $T(t,r) \rightarrow T_0 \widehat{T}_{1D}(r)$ and $P(t,r) \rightarrow P_0 \widehat{P}_{1D}(r)$
- Process applied to *LILAC* simulations using synthetic neutron and x-ray diagnostics to ensure bang time profiles are reproduced by this method

LILAC pressure versus _LILAC_ inferred pressure



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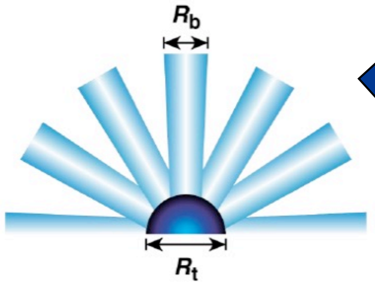
*Charles Cerjan, Paul T. Springer, *and* Scott M. Sepke , Physics of Plasmas 20, 056319 (2013)

Outline

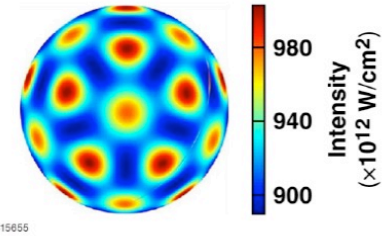
- Fusion performance metrics
- **Statistical mapping model**
- Target and laser pulse modifications and recent achievements

Statistical modeling of experimental data mapped onto simulated data is the main tool used to predict implosion performance and extract physical dependencies

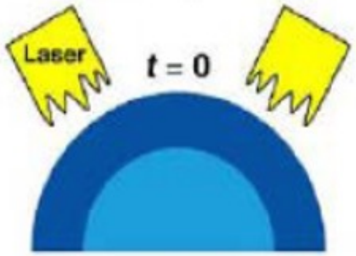
$$\mathrm{YOC}^{\mathrm{exp}} \equiv \frac{\mathrm{Yield}^{\mathrm{exp}}}{\mathrm{Yield}^{\mathrm{sim}}_{\mathrm{1D}}} \approx \mathrm{YOC}_{\mathrm{beam}}\left(\frac{R_b}{R_t},\mathrm{CR}\right)\mathrm{YOC}_{\mathrm{sw}}(\alpha,\mathrm{IFAR})\,\mathrm{YOC}_{L=1}\left(\frac{T^{\mathrm{max}}_{\mathrm{exp}}}{T^{\mathrm{min}}_{\mathrm{exp}}}\right)\mathrm{YOC}_{\mathrm{He3}}$$



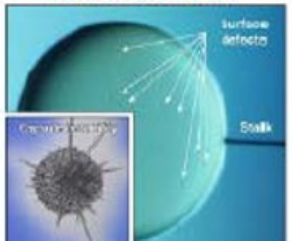
OMEGA illumination pattern*

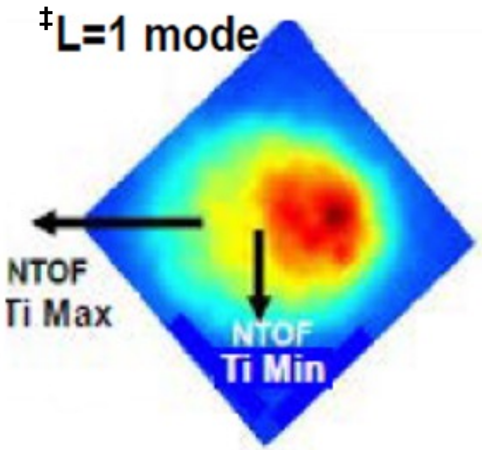


Laser imprinting

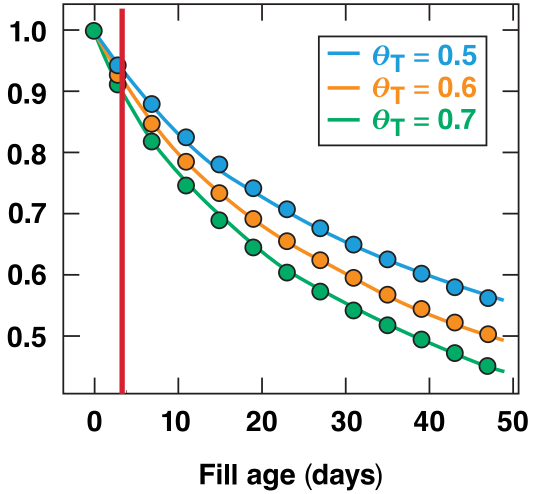


Isolated defects





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



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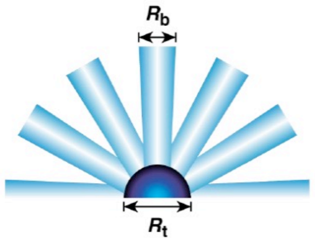
‡ O. M. Mannion *et al.*, Phys. Plasmas **28**, 042701 (2021)

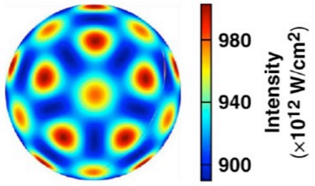
* V. Gopalaswamy *et. al*, Nature 565, 581–586 (2019).

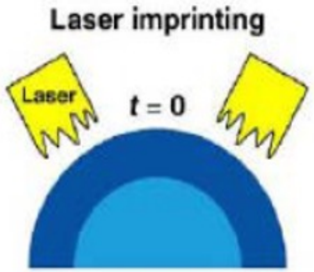
** A. Lees *et al*, Phys. Rev. Lett. 127, 105001 (2021).

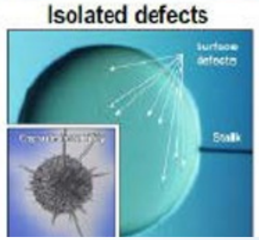
Degradation from short-wavelength perturbations and illumination nonuniformity determines the design space for targets and laser pulses



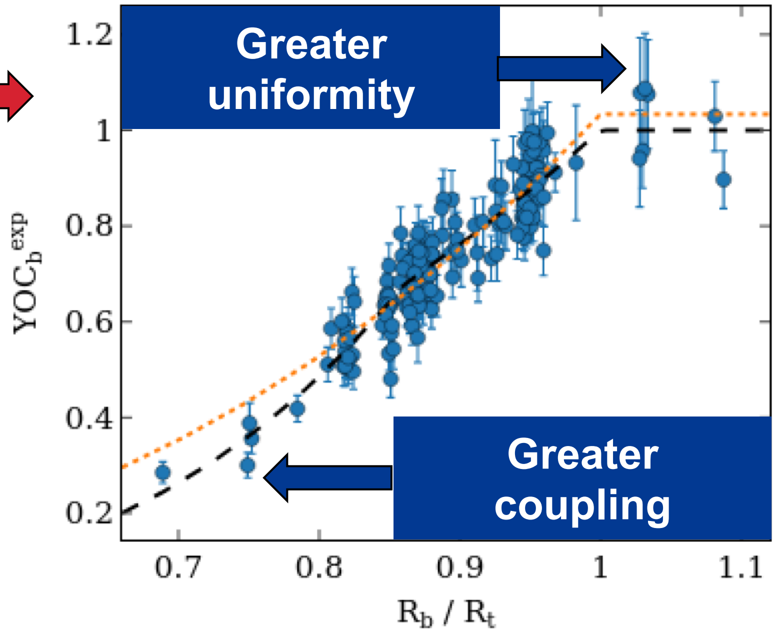
OMEGA illumination pattern*







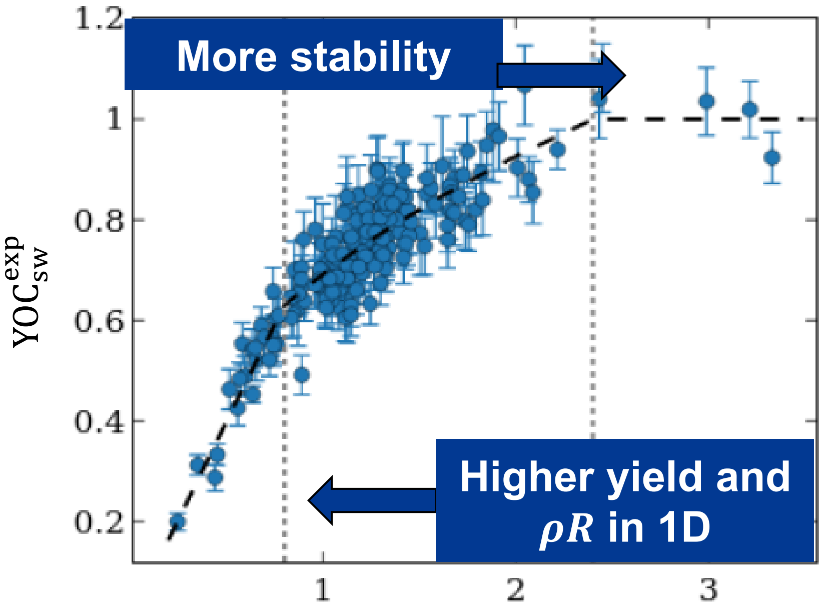
YOC$_b$ versus R_b/R_t



Greater uniformity

Greater coupling

YOC$_{sw}$ versus stability parameter



More stability

Higher yield and ρR in 1D

$$I_\alpha = \left(\frac{\alpha}{3}\right)^{1.1} \Big/ \left(\frac{IFAR}{20}\right)$$

Outline

- Fusion performance metrics
- Statistical mapping model
- **Target and laser pulse modifications and recent achievements**

Fusion energy is proportional to the product of hot-spot energy and Lawson parameter, placing a premium on improving the transfer of energy to the hot-spot

$$E_f \propto \varepsilon_\alpha \frac{P^2}{T^2}\langle\sigma v\rangle V\tau = E_{hs}\overbrace{\left(\frac{P\tau}{T^2/\varepsilon_\alpha\langle\sigma v\rangle}\right)}^{\sim\chi} \propto E_{hs}\chi$$

$$E_{hs} = E_L\left(\frac{E_{abs}}{E_L}\right)\left(\frac{E_k}{E_{abs}}\right)\left(\frac{E_{hs}}{E_k}\right)$$

MPD for higher IR → UV conversion
(from 28.5 kJ to 31.5 kJ)

η_{hs} — High IFAR

η_{abs} — Large outer diameter (OD) targets,
Si-doped ablators, MPD

η_{hydro} — Thin ice layers for greater rocket efficiency

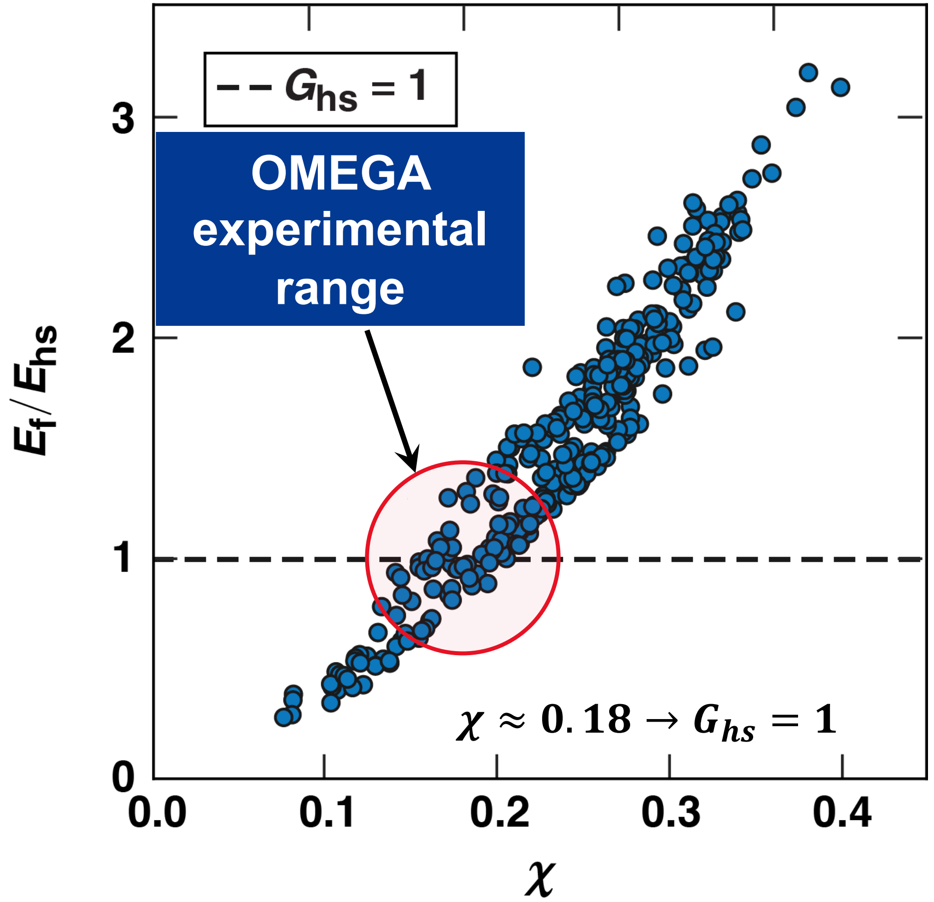
Optimization campaign: Optimize Lawson parameter χ
DT liner campaign: Maximize fusion yield on OMEGA by maximizing E_{hs}

The values of χ required for hotspot gain above unity are within range of current OMEGA DT-layered implosions

$$^{*}G_{hs} \equiv E_f/E_{hs}$$
$$G_{hs} \propto \chi$$

- The hotspot inference model on 1-D *LILAC* simulations shows that current OMEGA implosions with χ between 0.16 and 0.2 can access $G_{hs} > 1$

LILAC hot-spot gain versus χ



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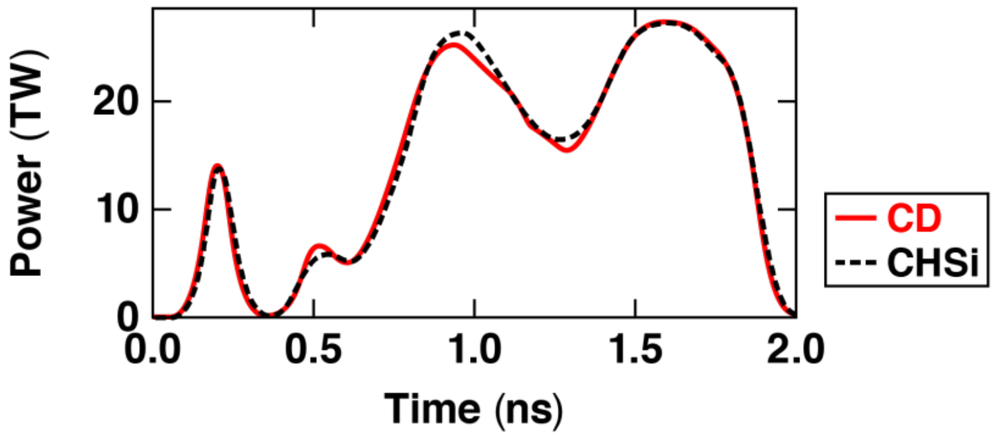
*Hot-spot corresponds to the region that produces 90% of the fusion yield

Laser-target energy coupling is enhanced by using silicon doping, larger OD targets, and multipulse-driver (MPD)

Laser power history



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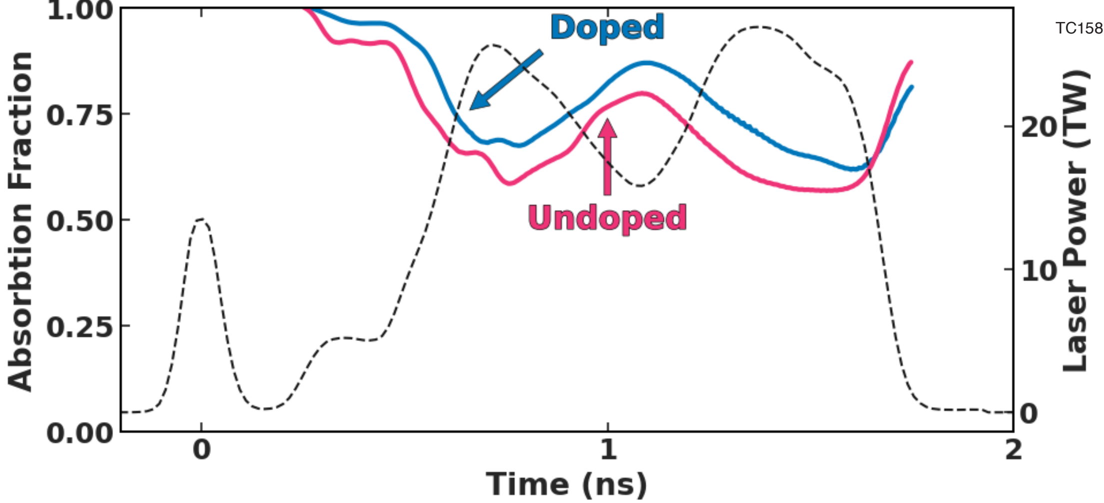
LILAC absorption fraction



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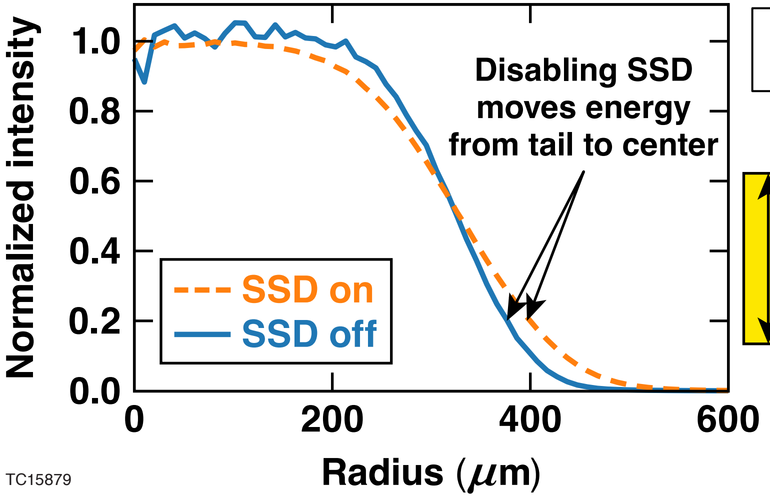
Beam profiles with SSD ON/OFF



$$E_{hs} = E_L \eta_{abs} \eta_{hydro} \eta_{hs}$$

R_b^P = 415 μm

Picket beam SSD on

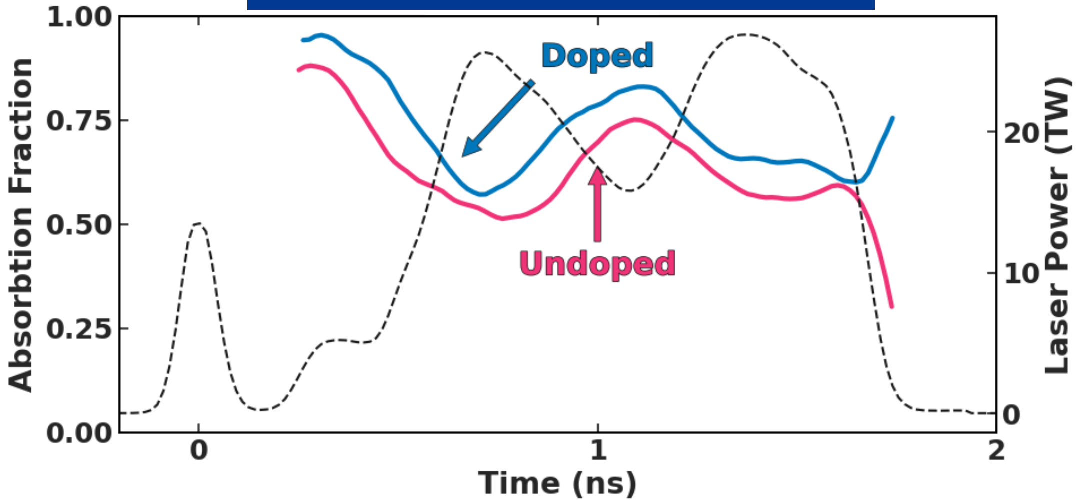
Drive beam SSD off

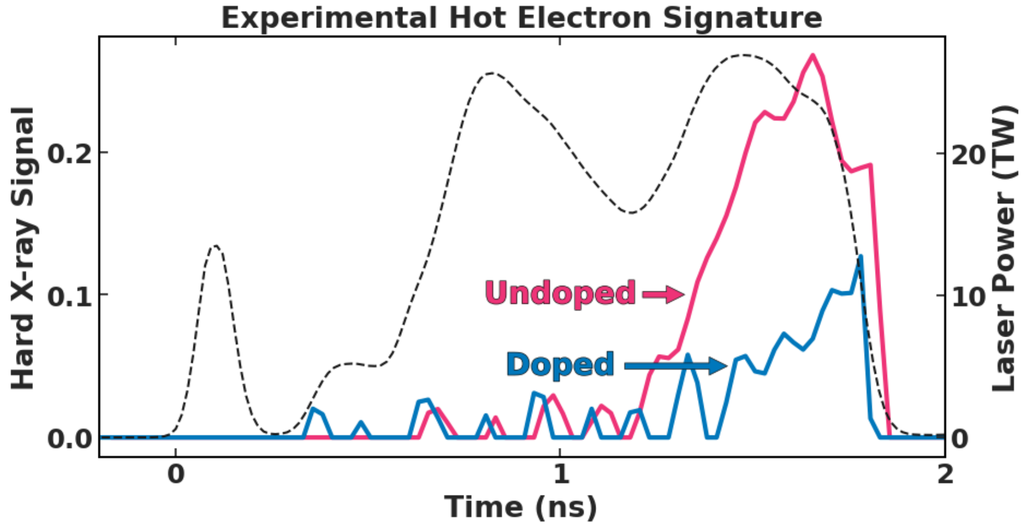
R_b^D = 375 μm

- MPD leads to higher energy on target (31 kJ versus 29 kJ) enhanced coupling at the cost of reduced R_b/R_t
- In 1-D simulations, V_{imp} increase is typically ~30 km/s from absorption and 30 km/s from extra available energy

Si-doping leads to higher absorption in experiment and suppresses hot electron production originating from two-plasmon decay

Experimental absorption fraction



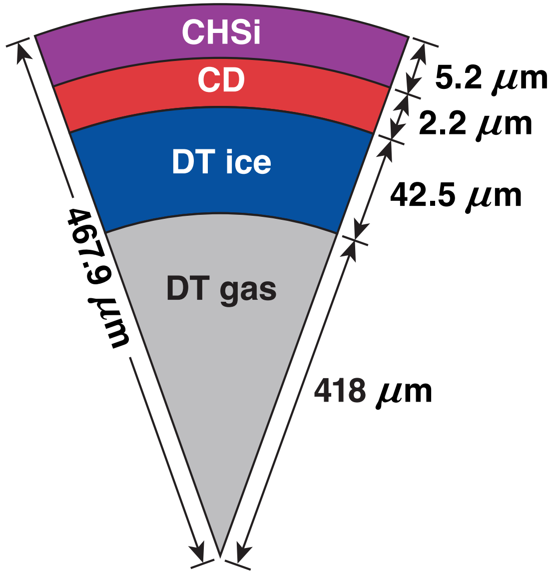


	CD (shot 99922)	CHSi (shot 101777)
Experimental yield	1.6×10^{14}	2.0×10^{14}
HXRD (pC)	195±24	53±16
Absorption	59±5%	69±5%

P. Farmakis *et al.*, CO04.00003,
V. Gopalaswamy *et al.*, CO04.00006, this conference.

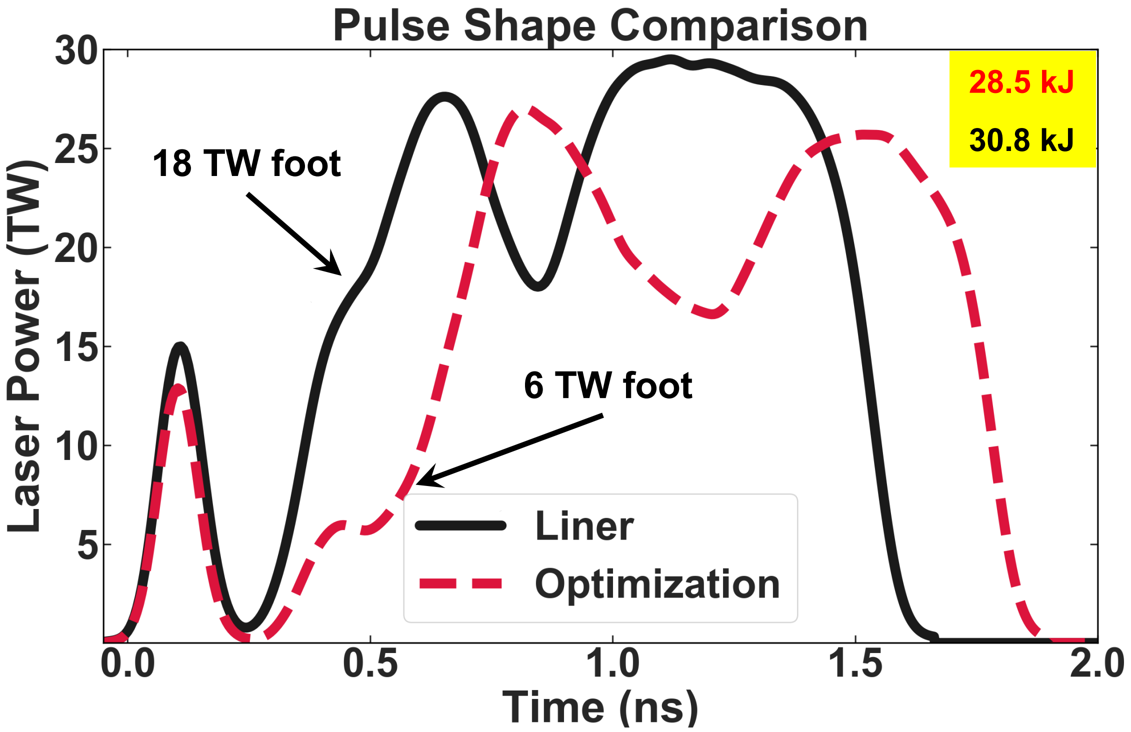
Thin-Ice DT liners can reach implosion velocities ~600 km/s but must be driven at high adiabats to maintain stability

Optimization campaign

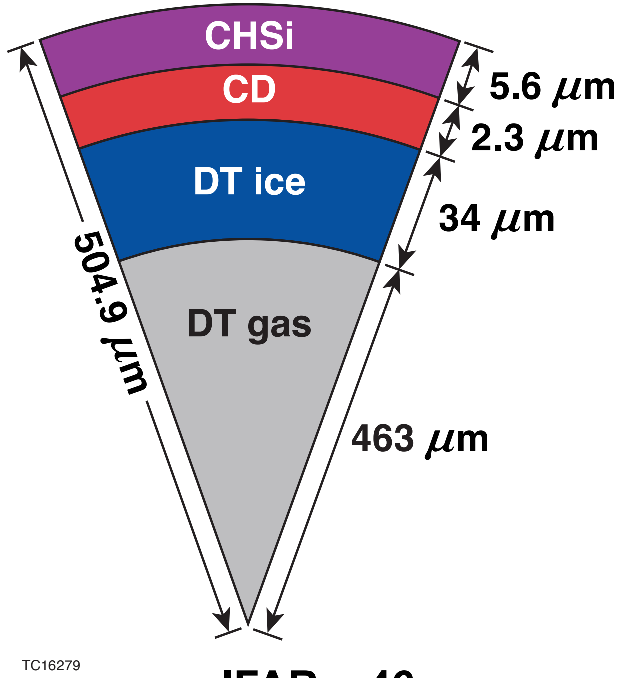


IFAR = 27
Adiabat = 5.2
V_{imp} = 450 to 500 km/s

$$E_{hs} = E_L \eta_{abs} \eta_{hydro} \eta_{hs}$$



DT liner campaign



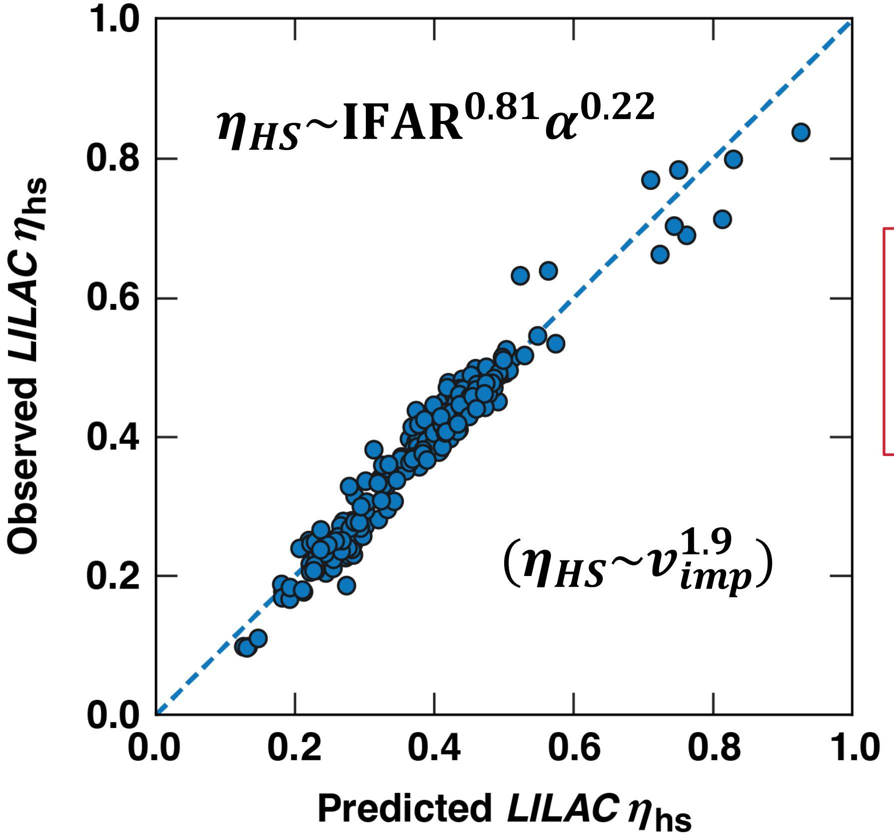
IFAR = 46
Adiabat = 8.7
V_{imp} = 550 to 600 km/s

C. A. Williams et al., "High yields in direct-drive inertial confinement fusion using thin-ice DT liner targets," Phys. Plasmas 28, 122708 (2021)

Converting shell kinetic energy to hot-spot internal energy is most efficient for high-IFAR, high-adiabat implosions

$$E_{hs} = E_L \eta_{abs} \eta_{hydro} \boldsymbol{\eta_{hs}}$$

Transfer efficiency predictive model in 1-D



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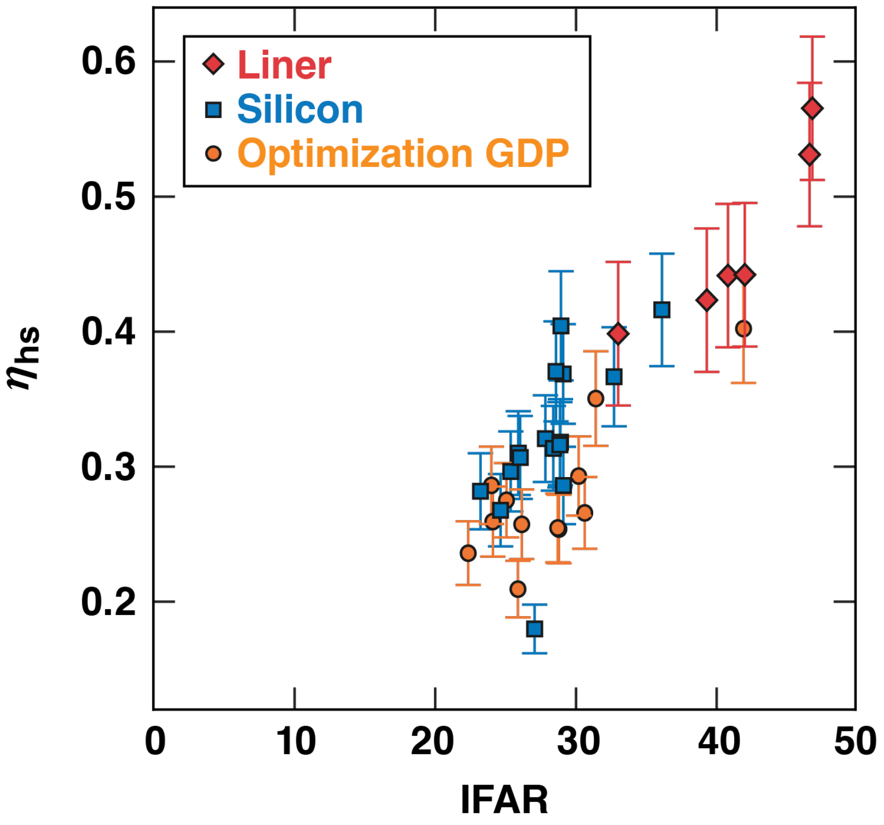
Pushing IFAR higher boosts both gross kinetic energy and transfer efficiency.

Experimental transfer efficiency versus IFAR



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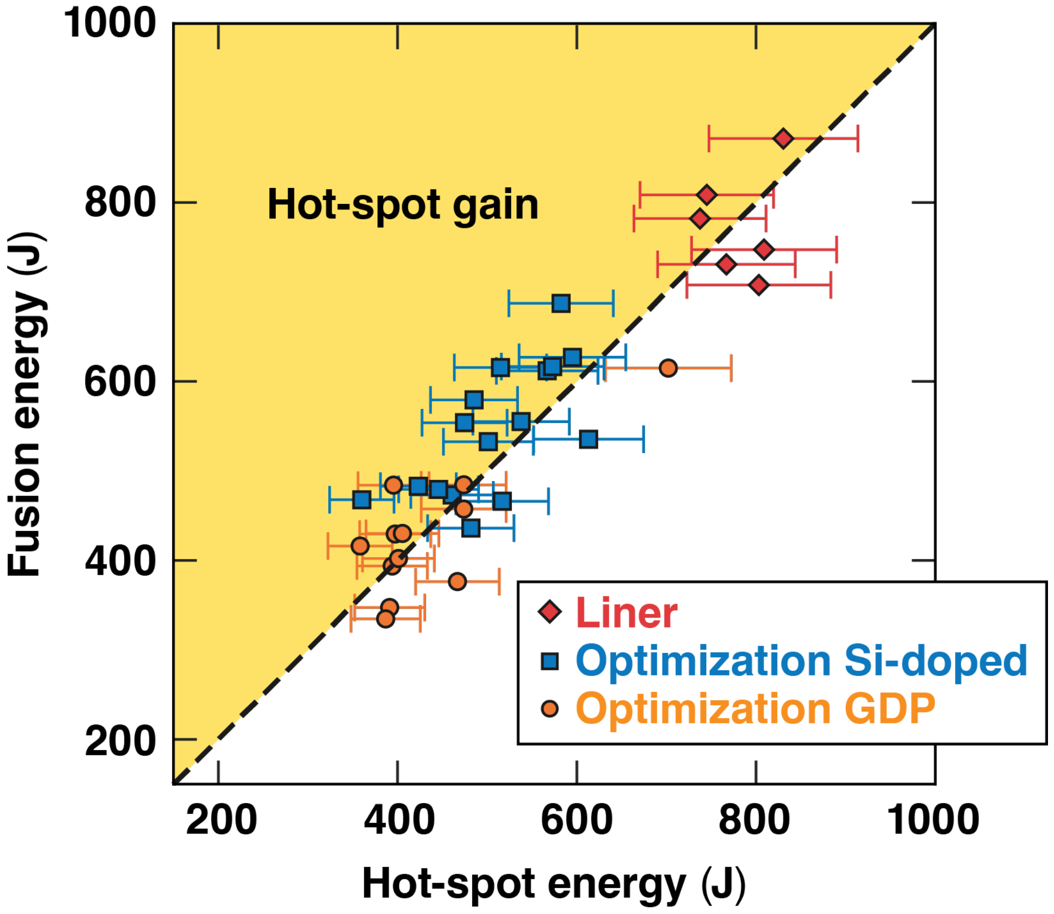
Recent high-performance implosions are the first to exhibit higher fusion energy than hot-spot internal energy

- **Hotspot gains $G_{HS} > 1$ were reached in recent shots**
- **Nearly all heating of hotspot comes from compression work (i.e., negligible alpha heating)**
- **Achieved with GDP plastic shells, Si-doped shells, and DT liners**



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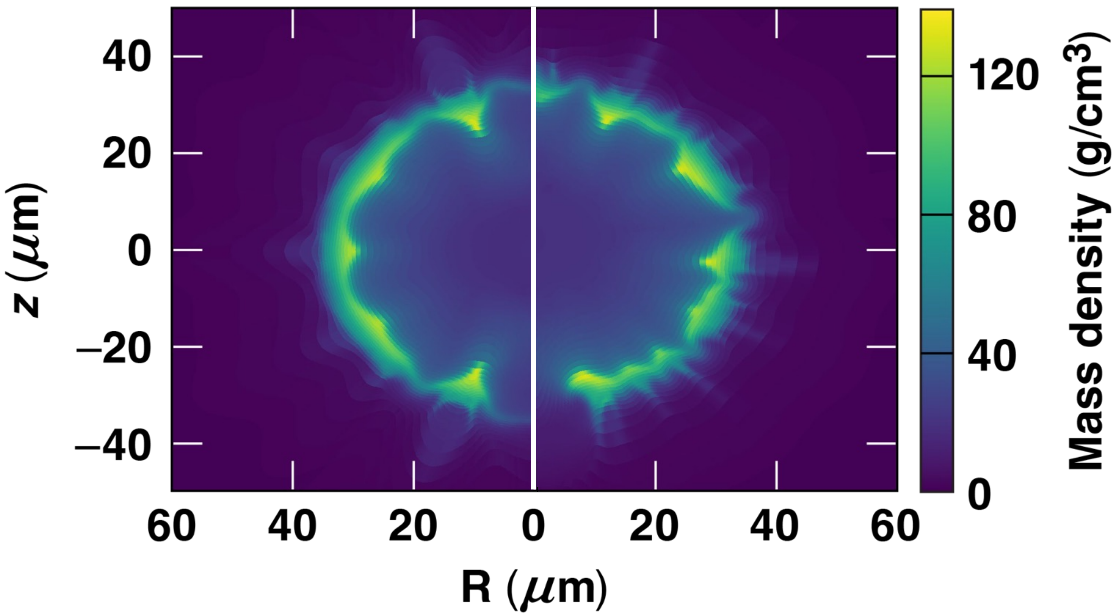
*C. A. Williams *et al.* in preparation

2-D Simulations of DT liner shots suggest laser imprint minimally affects implosion performance even at $\alpha \approx 6$ in agreement with statistical modeling

Mass density at bang Time



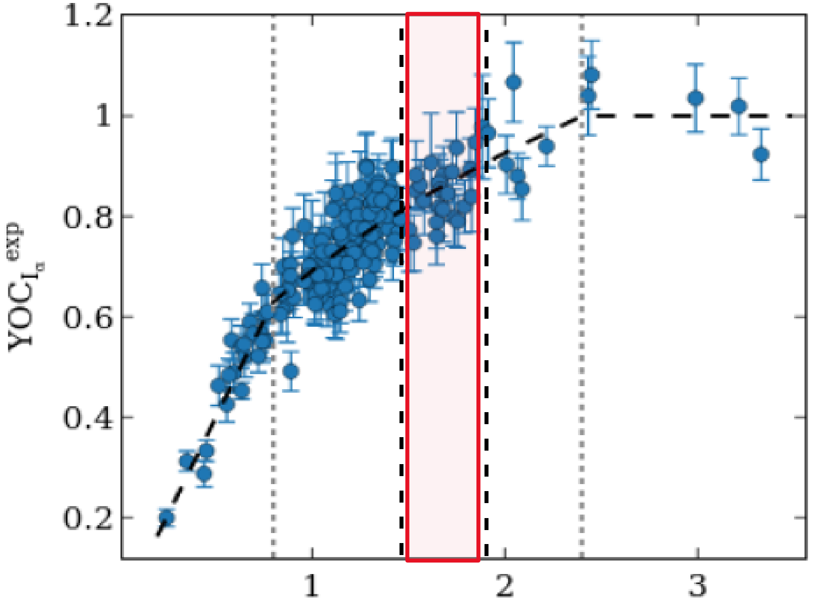
No Imprint

Yield = 1.02 × 10^{15}

Imprint up to mode 50

Yield = 1.02 × 10^{15}

YOC$_{sw}$ versus stability parameter

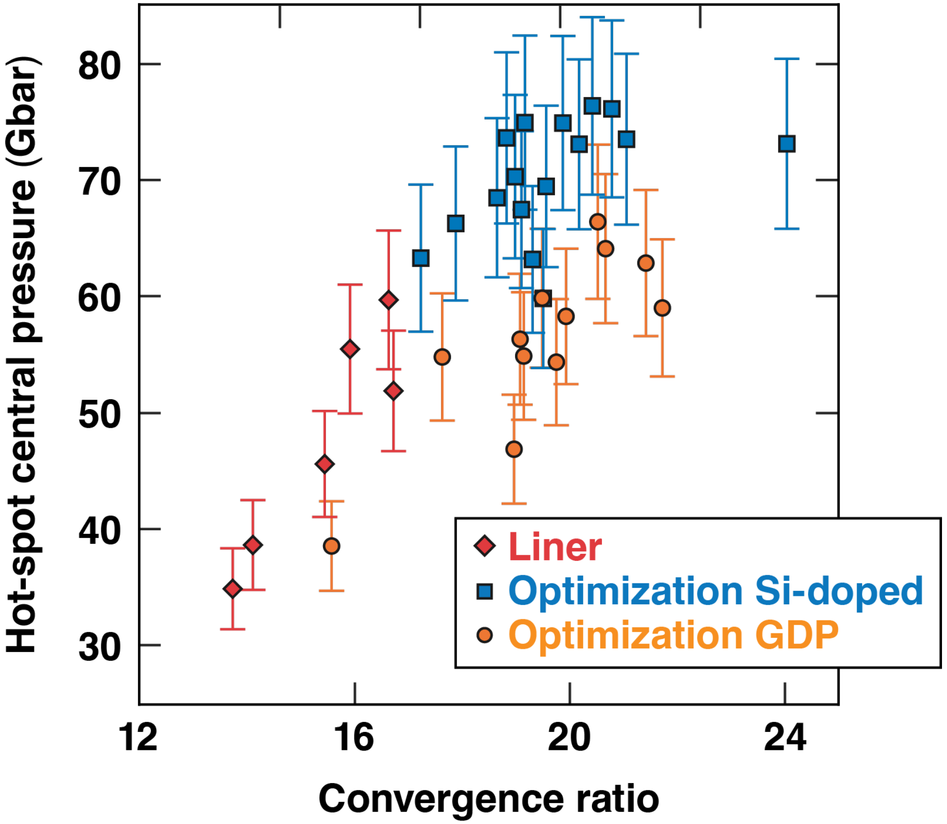


$$I_\alpha = \left(\frac{\alpha}{3}\right)^{1.1} \Big/ \left(\frac{IFAR}{20}\right)$$

Both liners and χ-optimization shots live in the shaded region.

Hot-spot pressures approaching 80 Gbar are reached in optimization shots, while DT liners demonstrate the highest yields at the lowest convergence ratios

Inferred hot-spot pressure versus convergence ratio



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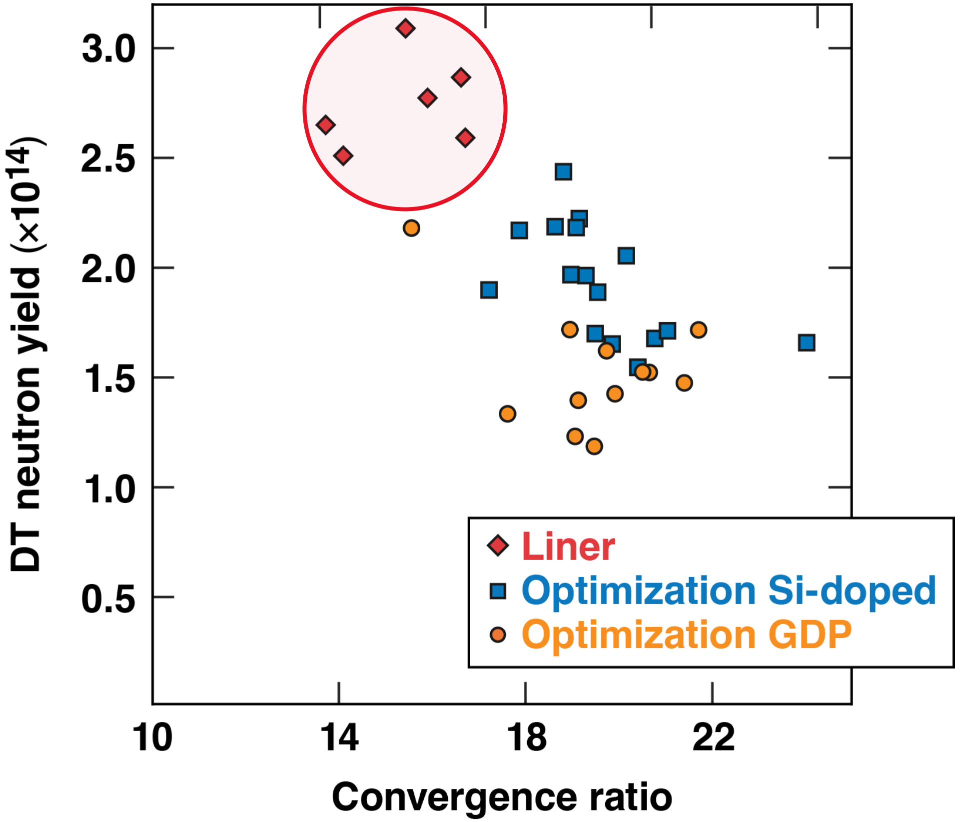
Neutron yield versus convergence ratio



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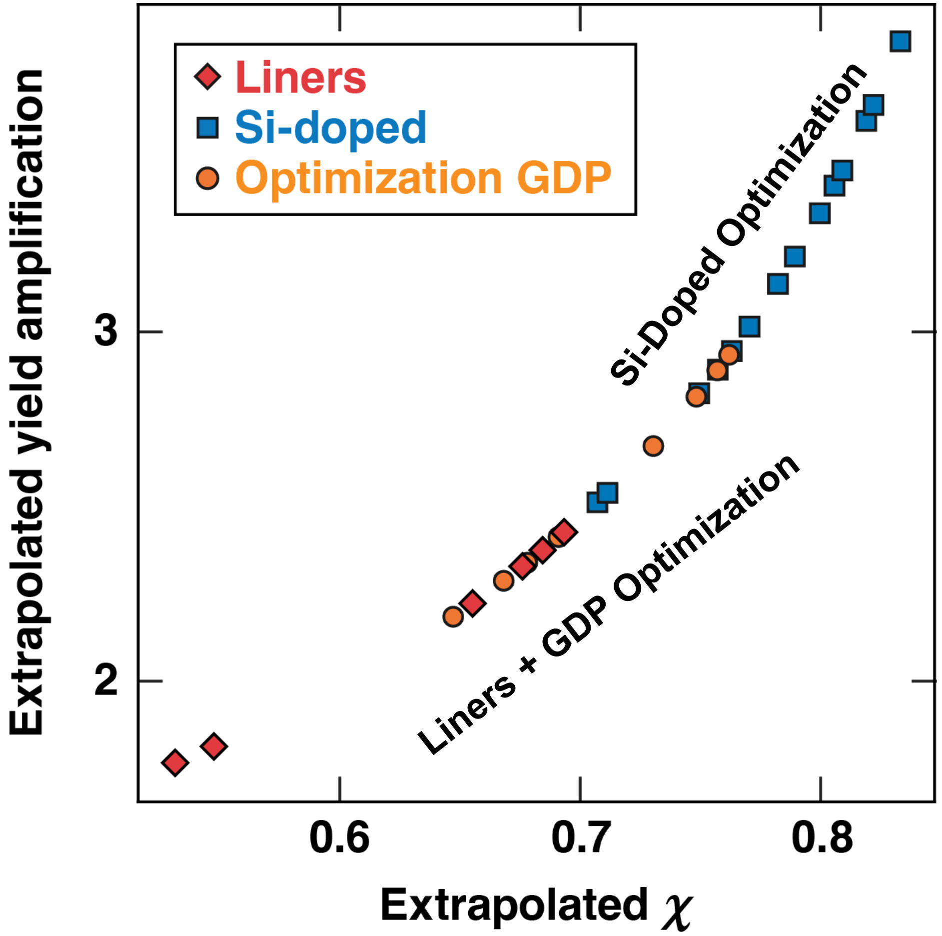
DT liners provide a platform to achieve the highest yields with robust hydrodynamic stability.

Liners do not reach the same level of extrapolated yield amplification as optimization shots due to lower convergence

Extrapolated yield amplification versus extrapolated χ



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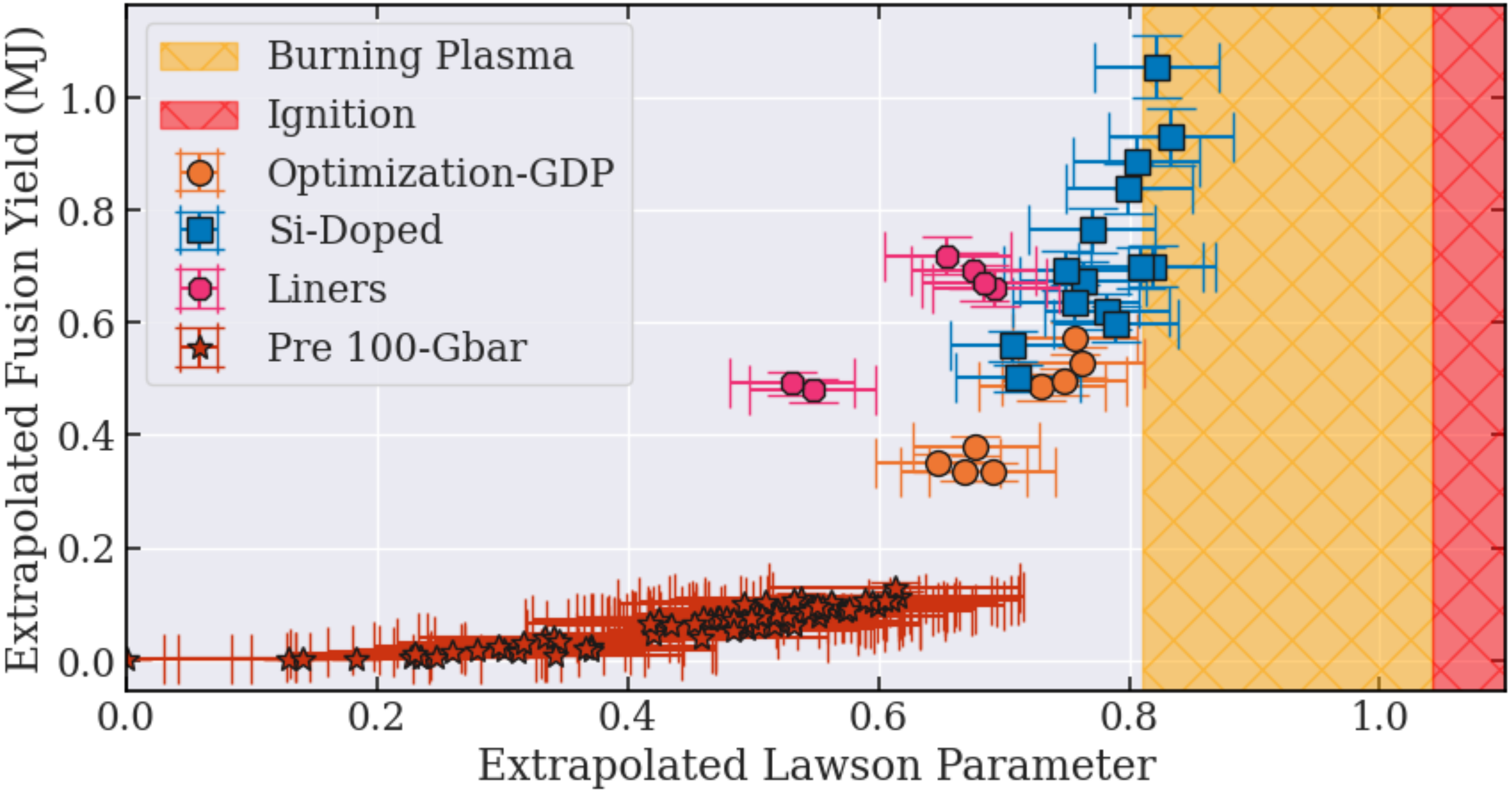
Increased coupling has produced several shots that hydroscale into the burning plasma regime

2-MJ symmetric drive hydroscaling



V. Gopalaswamy *et al.*, CO04.00006, this conference.

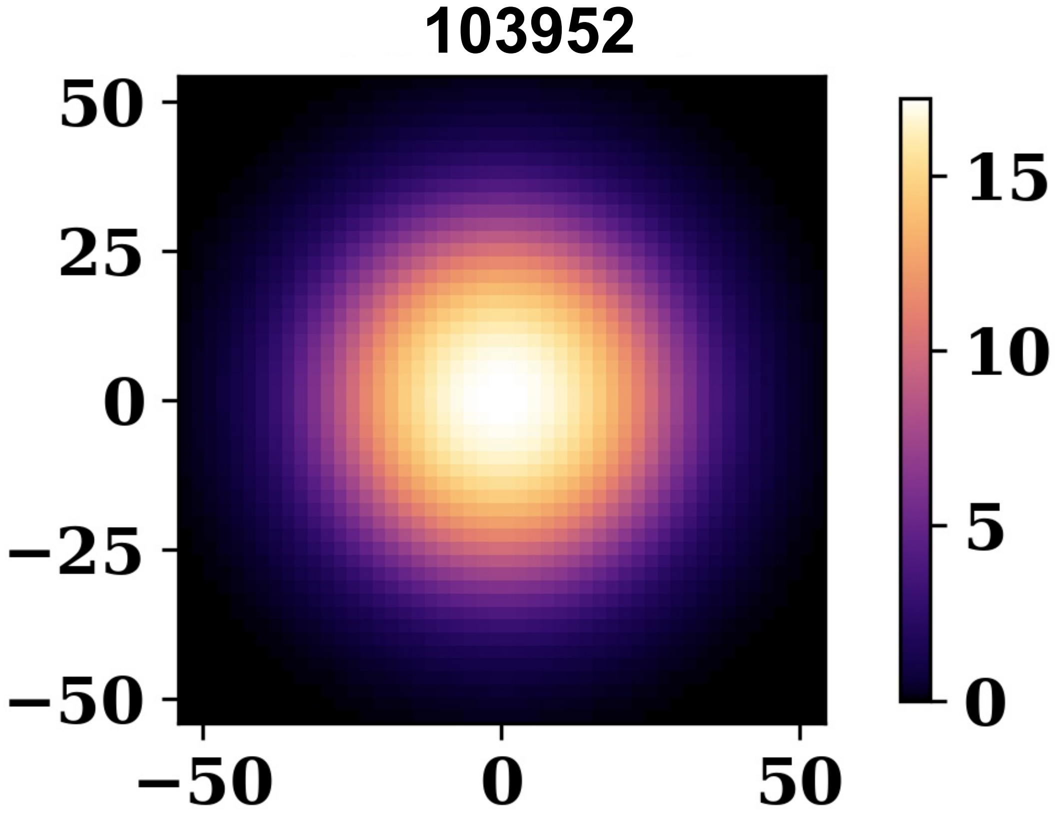
Summary/Conclusions

Recent OMEGA implosions have achieved fuel gains >1 and record fusion yields above 3×10^{14}

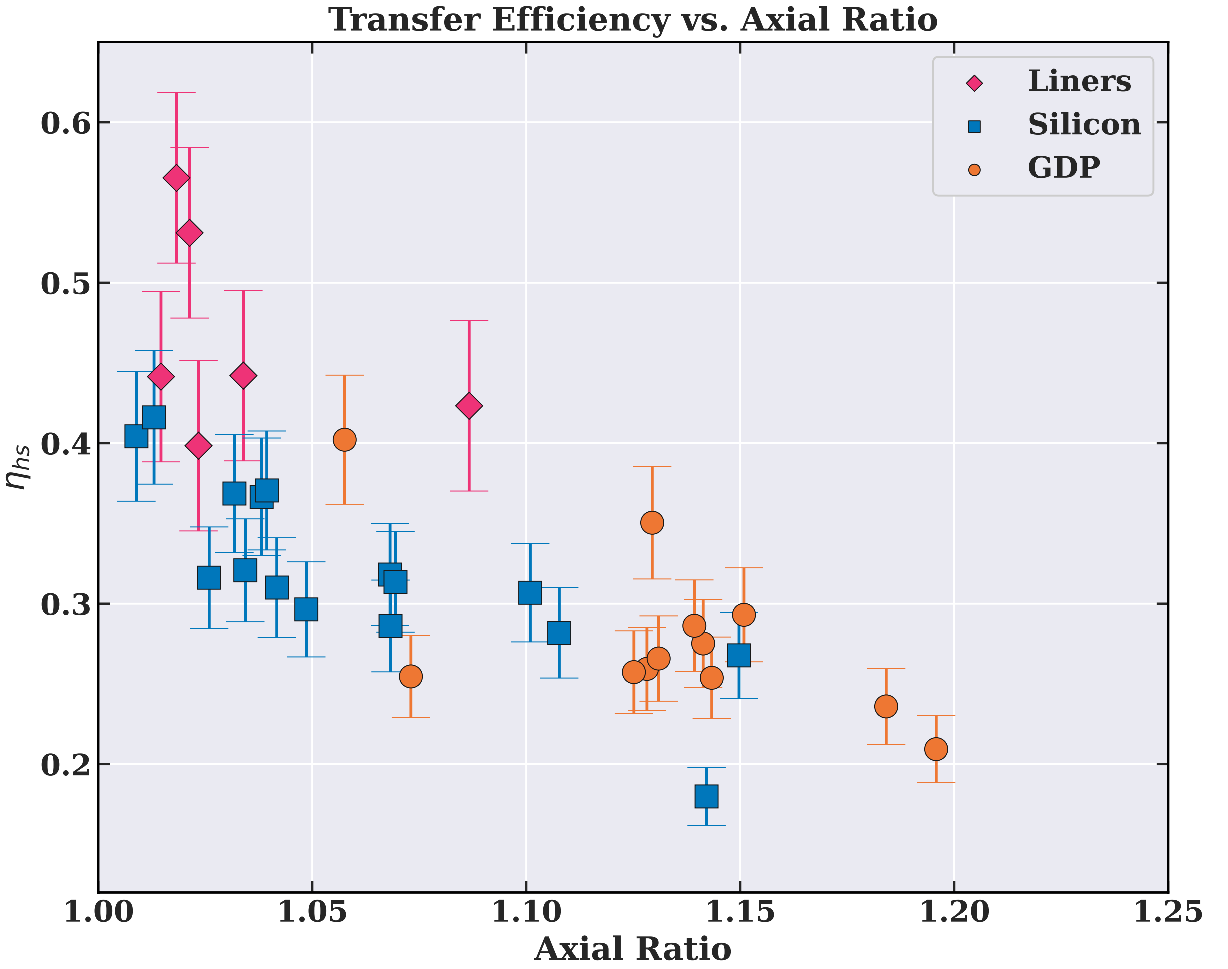
- **Highest yields on OMEGA (3.1×10^{14}) achieved using low-convergence, high-velocity (~600 km/s) DT liners**
- **1st demonstration of fusion energy exceeding hot-spot energy in SDD* using both high CR** targets and liners**
- **Silicon doping and multipulse-driver (MPD) show enhanced laser-to-target coupling**
- **Pressures near 80 Gbar reached with highest hydroscaled χ (0.83) at 2 MJ of laser energy, corresponding to the burning plasma regime**

Supplemental Slides

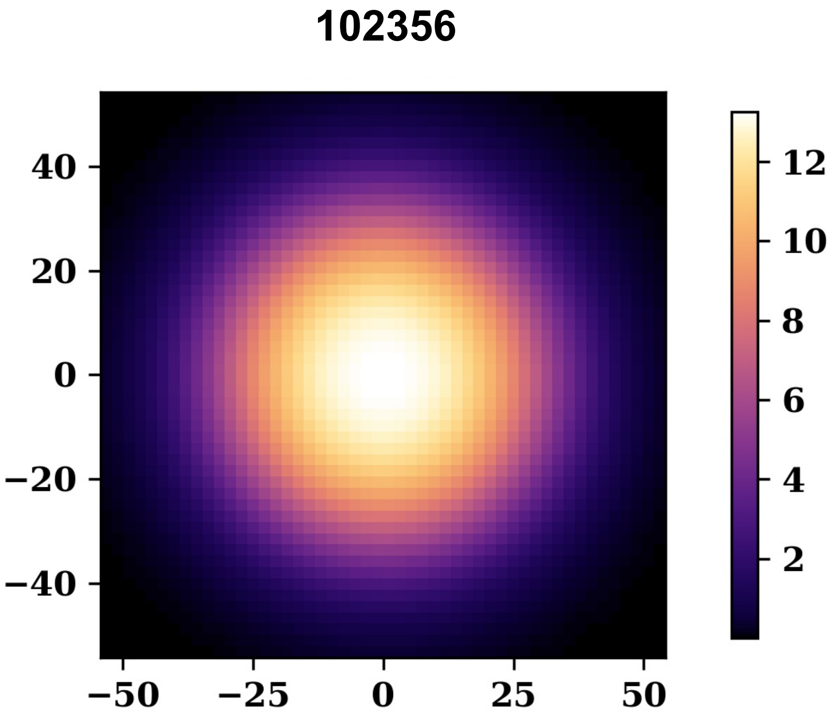
Introduction of silicon and MPD appear to mitigate the L=2 perturbation, generating rounder hot spots and more conversion to hot-spot energy



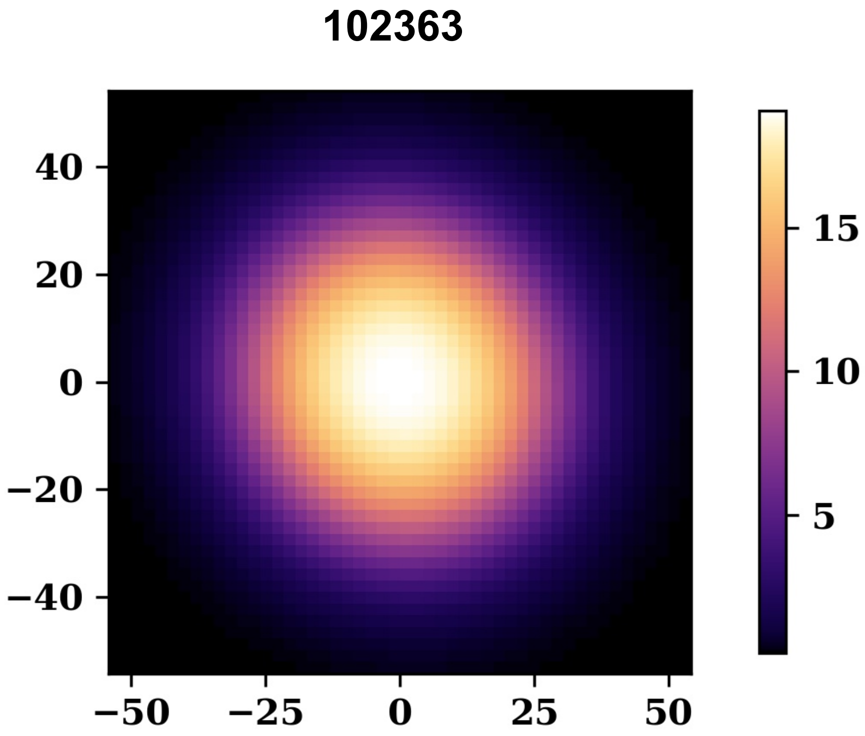
a/b = 1.01



Experimental hot spot x-ray images show liner compression responds to changes in ablator composition and thickness


102356

7.2 µm CD
R0 = 34.6 µm
$\alpha = 7.7$


102363

5.6 µm CHSi + 2.3 µm CD
R0 = 30.8 µm
$\alpha = 8.7$

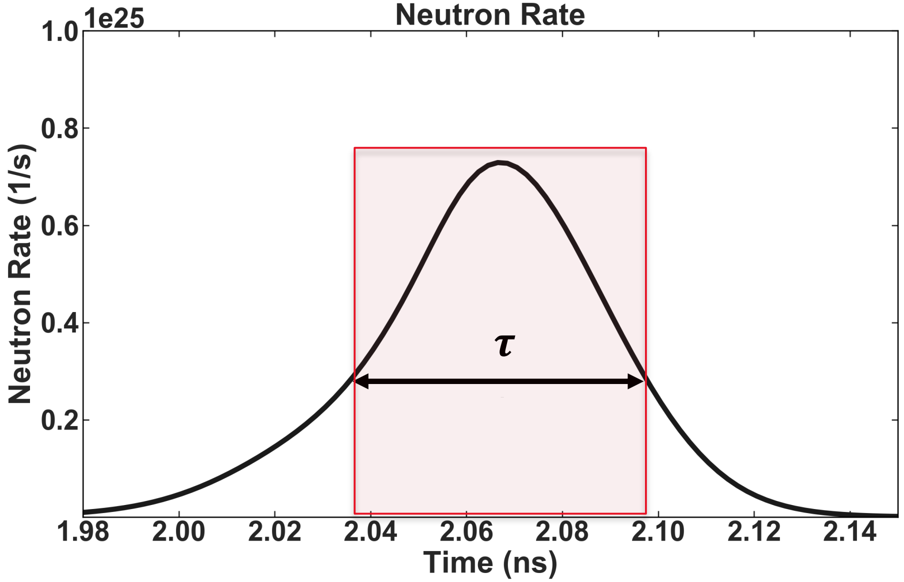
Hot-spot Model

$$Y = f_D f_T \int dt \int_0^{R_{hs}} d^3r \frac{P_i^2}{T_i^2} \langle \sigma v \rangle$$

$$E^{\mathrm{hs}} = \sqrt{\frac{9\pi Y}{f_{\mathrm{D}} f_{\mathrm{T}} \tau}} R_{17}^{3/2} k_{\mathrm{B}} \langle T_{\mathrm{i}} \rangle \frac{\sqrt{\int_0^1 x^2 \left(\hat{P}_{\mathrm{i}}^2/\hat{T}_{\mathrm{i}}^2\right) \langle \sigma v \rangle \, \mathrm{d}x}}{\int_0^1 x^2 \left(\hat{P}_{\mathrm{i}}^2/\hat{T}_{\mathrm{i}}\right) \langle \sigma v \rangle \, \mathrm{d}x} \left[\int_0^1 x^2 \hat{P}_{\mathrm{i}} \, \mathrm{d}x + \frac{\langle T_{\mathrm{e}} \rangle}{\langle T_{\mathrm{i}} \rangle} \frac{\int_0^1 x^2 \left(\hat{P}_{\mathrm{i}}^2/\hat{T}_{\mathrm{i}}\right) \langle \sigma v \rangle \, \mathrm{d}x}{\int_0^1 x^2 \hat{P}_{\mathrm{e}} \left(\hat{P}_{\mathrm{i}}/\hat{T}_{\mathrm{i}}\right) \langle \sigma v \rangle \, \mathrm{d}x} \int_0^1 x^2 \hat{P}_{\mathrm{e}} \, \mathrm{d}x \right]$$

$$\tau \to \tau' \approx 1.1\tau$$

Constraining hotspot properties using the yield and FWHM of the neutron rate (the burn width, τ) is equivalent to saying the red shaded area is equal to the total area of the curve.



This introduces a correction factor of

$$\left[2\sqrt{\frac{ln(2)}{\pi}}\right]^{-1} \approx 1.06$$

There is an additional correction coming from the fact that $\dot{Y}$ is not truly gaussian.