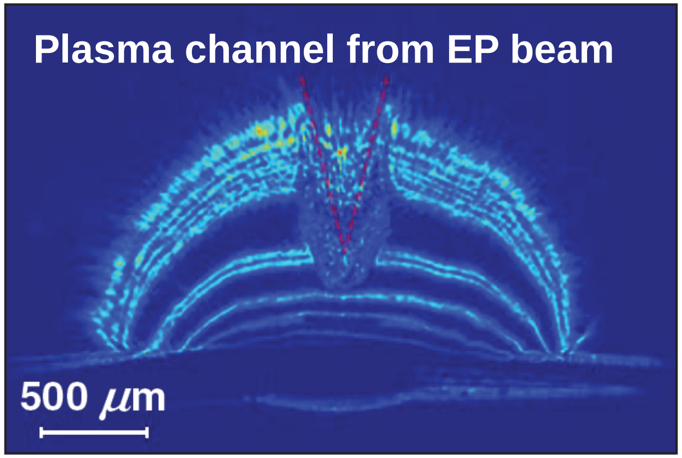
Direct Drive and Alternate Approaches for Laser Inertial Confinement Fusion (ICF)



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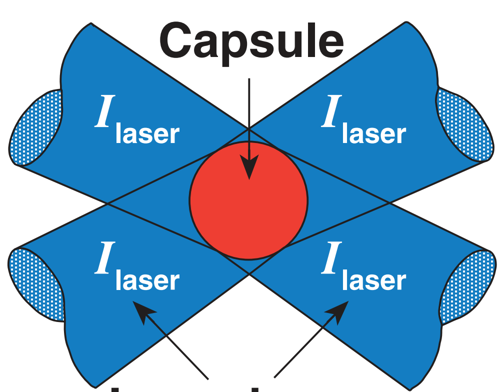
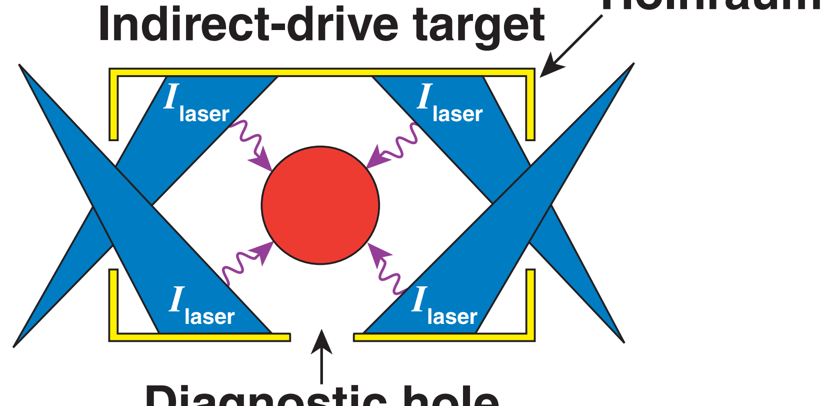
AAAS Meeting
Boston, MA
14–17 February 2013

Direct-drive ignition is the main thrust in LLE fusion research activities

- Fusion research at LLE is focused on building the foundations for a direct-drive–ignition demonstration at the National Ignition Facility (NIF)
- LLE is interested in the fusion-energy applications of inertial confinement fusion (ICF), but it is currently concentrating its efforts on demonstrating thermonuclear ignition of DT fuel
- Producing a burning plasma in the laboratory for the first time
  - is a grand scientific challenge ("a star on earth")
  - has great scientific value in astrophysics, nuclear, and plasma physics
  - has important implications for national security (Stockpile Stewardship)
  - represents the fundamental block of fusion-energy development by showing that fusion has the potential to be a viable energy source

Direct- and indirect-drive ICF aim to ignite a DT plasma by imploding capsules with on-target applied pressures of ~100 Mbar





$$P_A(\text{Mbar}) \sim 100\left(I_{\text{laser}}^{\text{PW/cm}^2}\right)^{2/3}$$

$$P_A(\text{Mbar}) \sim 100\left(\frac{T_{\text{rad}}^{\text{eV}}}{300}\right)^4$$

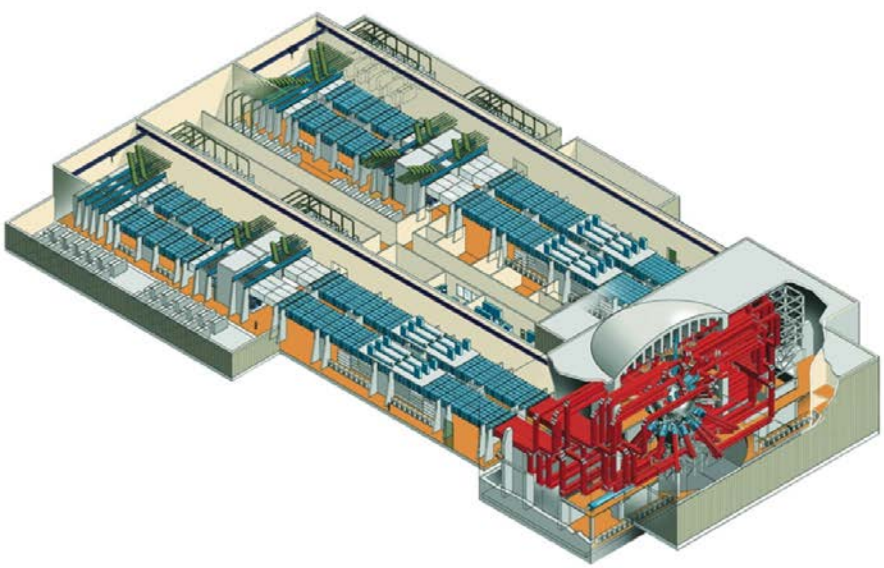
- More energy coupled to the target
- Less-uniform driver

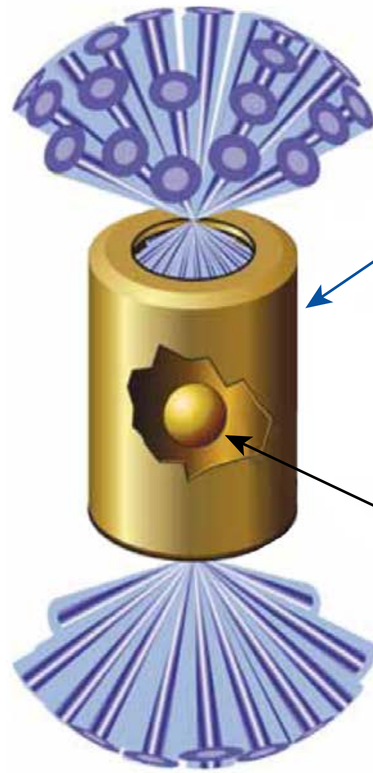
- Less energy coupled to the target
- More-uniform driver

I1371d

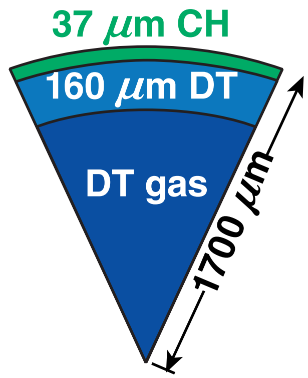
NIF is currently configured in a polar-drive setting for indirect-drive ignition; this is *not* an optimal configuration for direct drive that requires spherical illumination

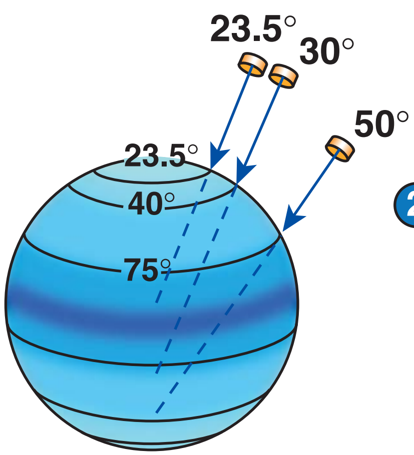
- The National Ignition Facility (NIF) at LLNL delivers ~2-MJ UV light at ~500 TW

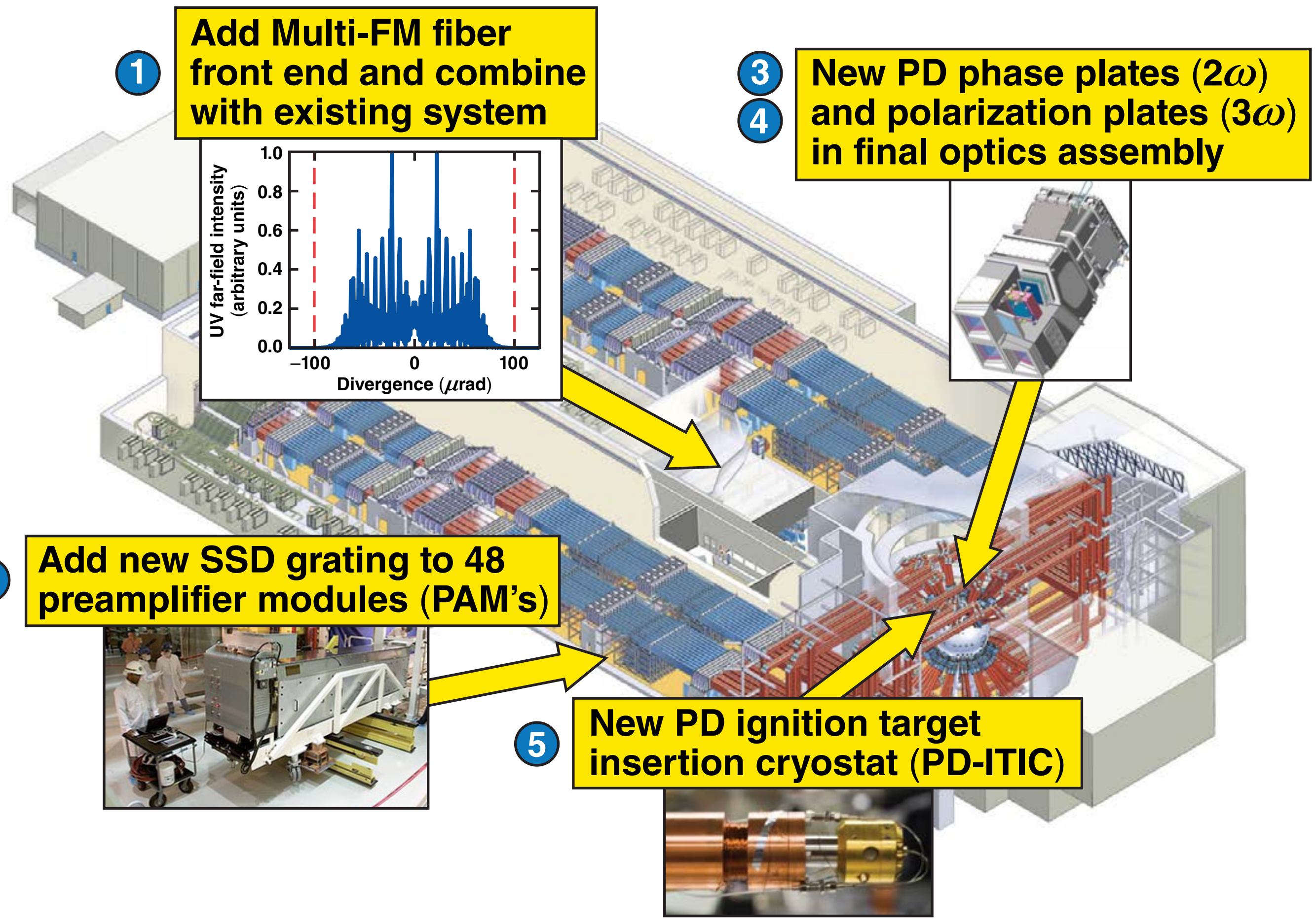




Polar-drive–ignition experiments on the NIF requires beam repointing and upgrades to the laser system





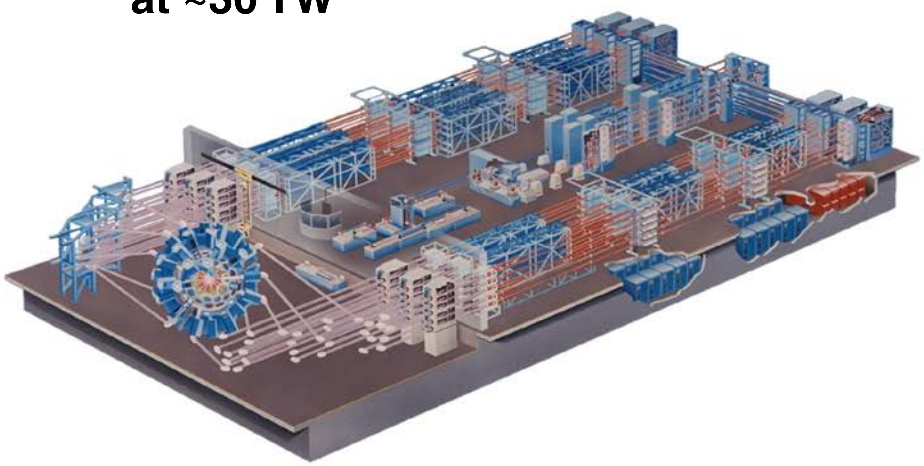


The laser technology required for polar-drive ignition on the NIF using a NIF PAM is being demonstrated on OMEGA EP.

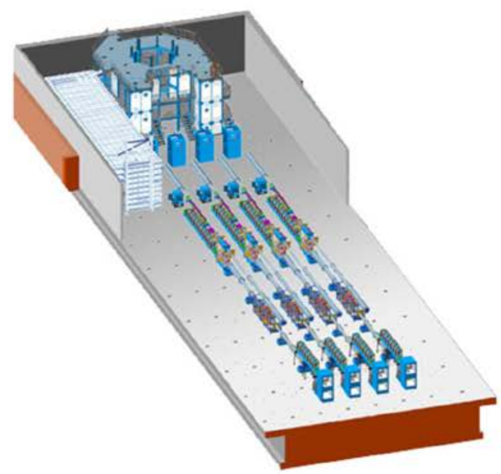
E19668m

OMEGA is currently the premiere facility for direct-drive experiments; it is coupled to a high-power, short-pulse laser (OMEGA EP) to explore advanced ignition and radiography

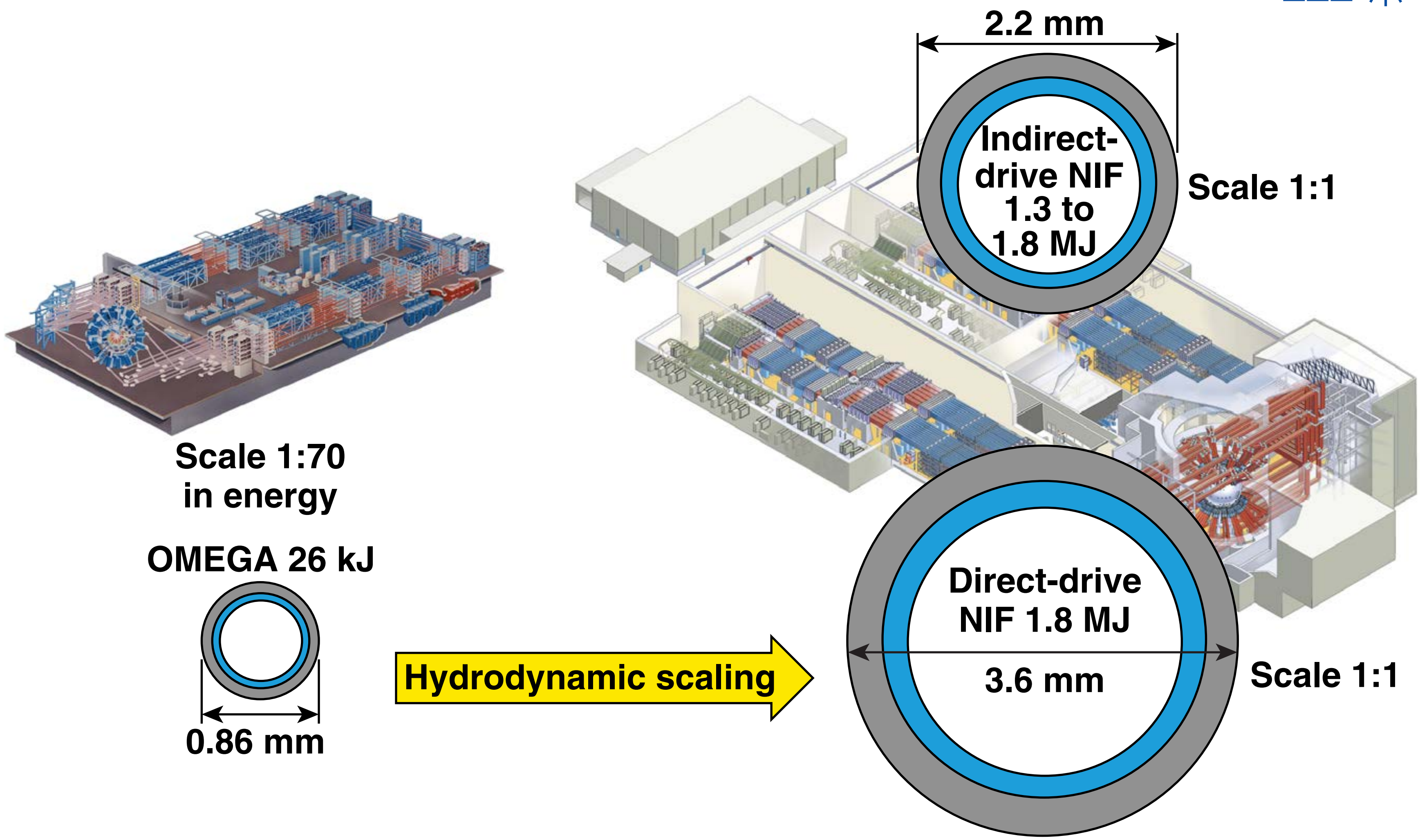
The OMEGA laser at the University of Rochester's Laboratory for Laser Energetics (LLE) delivers ~30-kJ UV light at ~30 TW



The OMEGA EP laser delivers ~2-kJ IR light in 10 ps (~2 PW) and 20-kJ light in UV-ns pulses



The NIF is currently pursuing indirect-drive ignition; to assess the prospects for direct-drive ignition, OMEGA results are scaled to NIF energies



Hydro-equivalent ignition on OMEGA

Like in Magnetic Confinement Fusion, the Lawson criterion determines the ICF ignition condition. In ICF, ignition occurs in the central hot spot

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α-particle heating rate > energy loss rate

$$\frac{\varepsilon_\alpha}{4} n^2 \langle \sigma v \rangle > \frac{3}{2}\frac{P}{\tau}$$

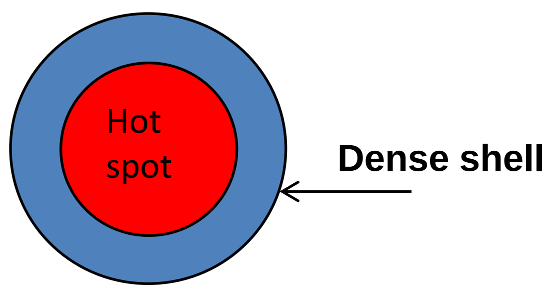
- 3.5MeV → ε_α
- n: ion particle density
- $\langle \sigma v \rangle$: fusion reactivity
- P: Plasma pressure
- τ: Energy confinement time

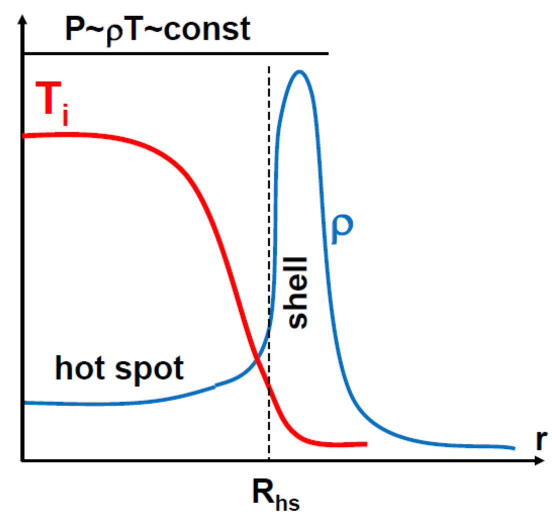
Ignition parameter → $\chi \equiv \dfrac{P\tau}{24\langle \sigma v \rangle \varepsilon_\alpha / T^2}$

Ignition condition → $\chi > 1$

LLNL Performance Parameter*

$$\mathrm{ITFx} \approx \chi^3$$

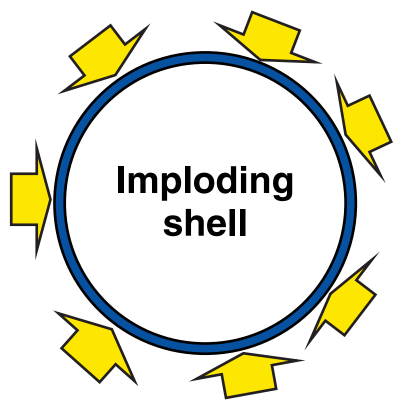




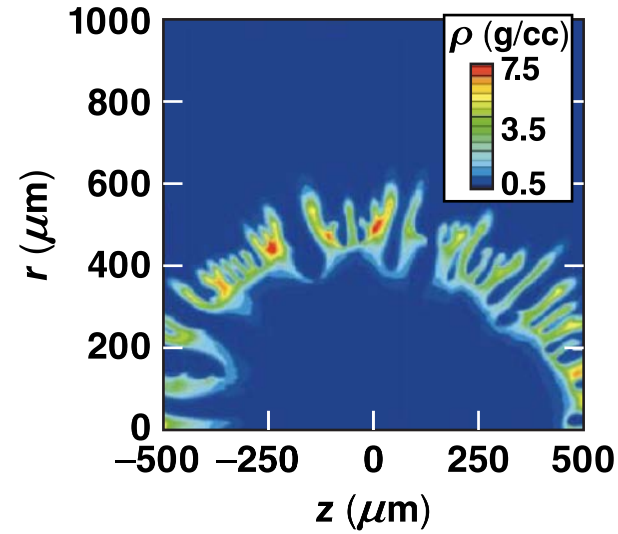
*B. K. Spears *et al.*, Phys. Plasmas 19, 056316 (2012).

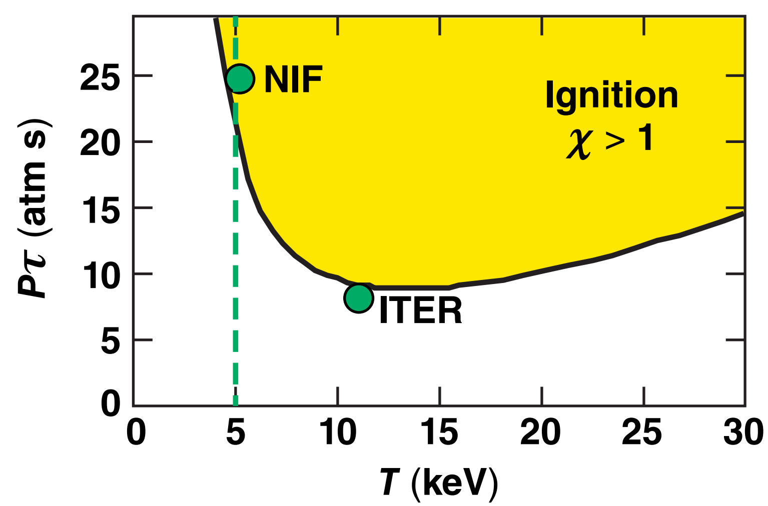
ICF implosions cannot achieve ~10-keV temperatures through compression alone

- High T requires high implosion velocity V_i
- High V_i requires thin shells
- Thin shells break up in flight because of hydrodynamic instabilities



$T \sim V_i$

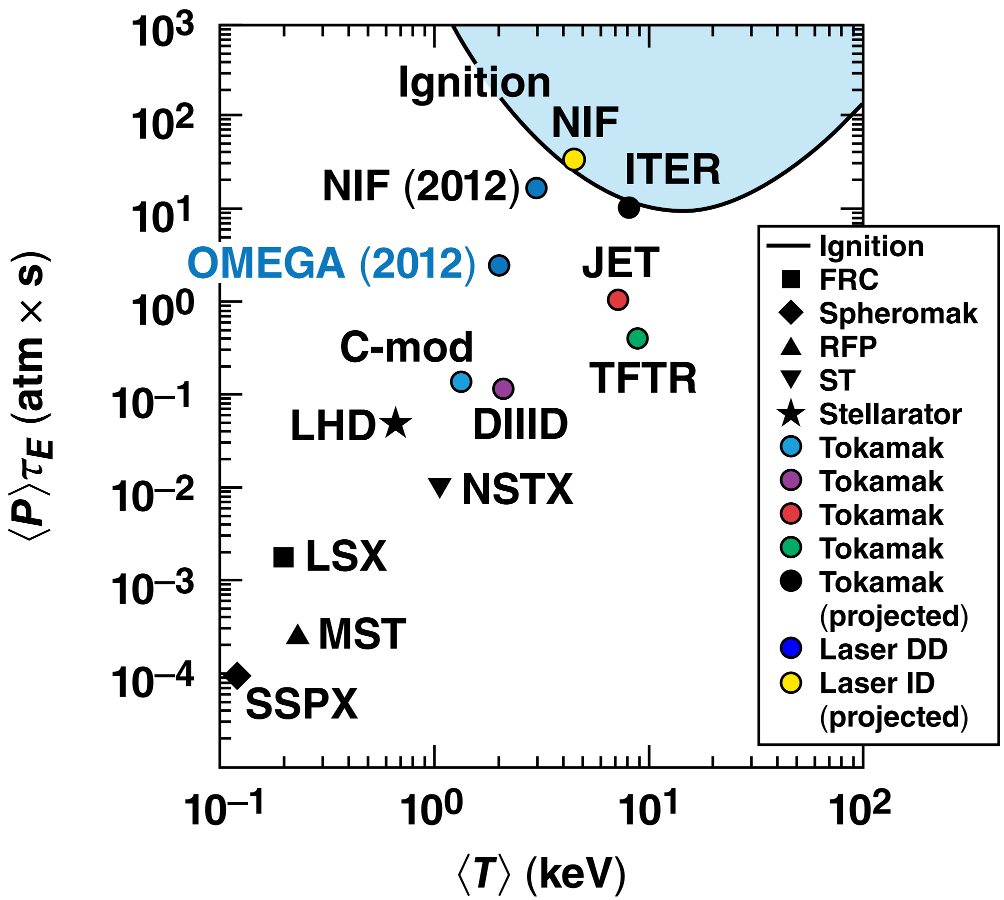




ICF must ignite at ~5 keV, requiring $V \sim 400$ km/s and $P\tau > 25$ atm s.

TC10258

The Lawson plot shows the performance of fusion devices with respect to thermonuclear ignition (not fusion energy)



TC8678e

R. Betti *et al*., Phys. Plasmas 17, 058102 (2010).

Hydrodynamic similarity provides a tool for estimating the energy scaling of implosion performance

- Scaling of ignition parameter ($\chi > 1$ for ignition)

$$\chi \approx \chi_{\mathrm{ref}}\left(V_{\mathrm{i}}, \alpha, I_{\mathrm{laser}}, \frac{\sigma_{\mathrm{rms}}}{R_{\mathrm{target}}}\right)\left(\frac{E_{\mathrm{laser}}}{E_{\mathrm{laser}}^{\mathrm{ref}}}\right)^{0.4}$$

V_{i} = shell implosion velocity, α = shell entropy $\left(\sim P / \rho^{5/3}\right)$,
I_{L} = laser intensity, σ_{rms} = amplitude of nonuniformities, R_t = target radius

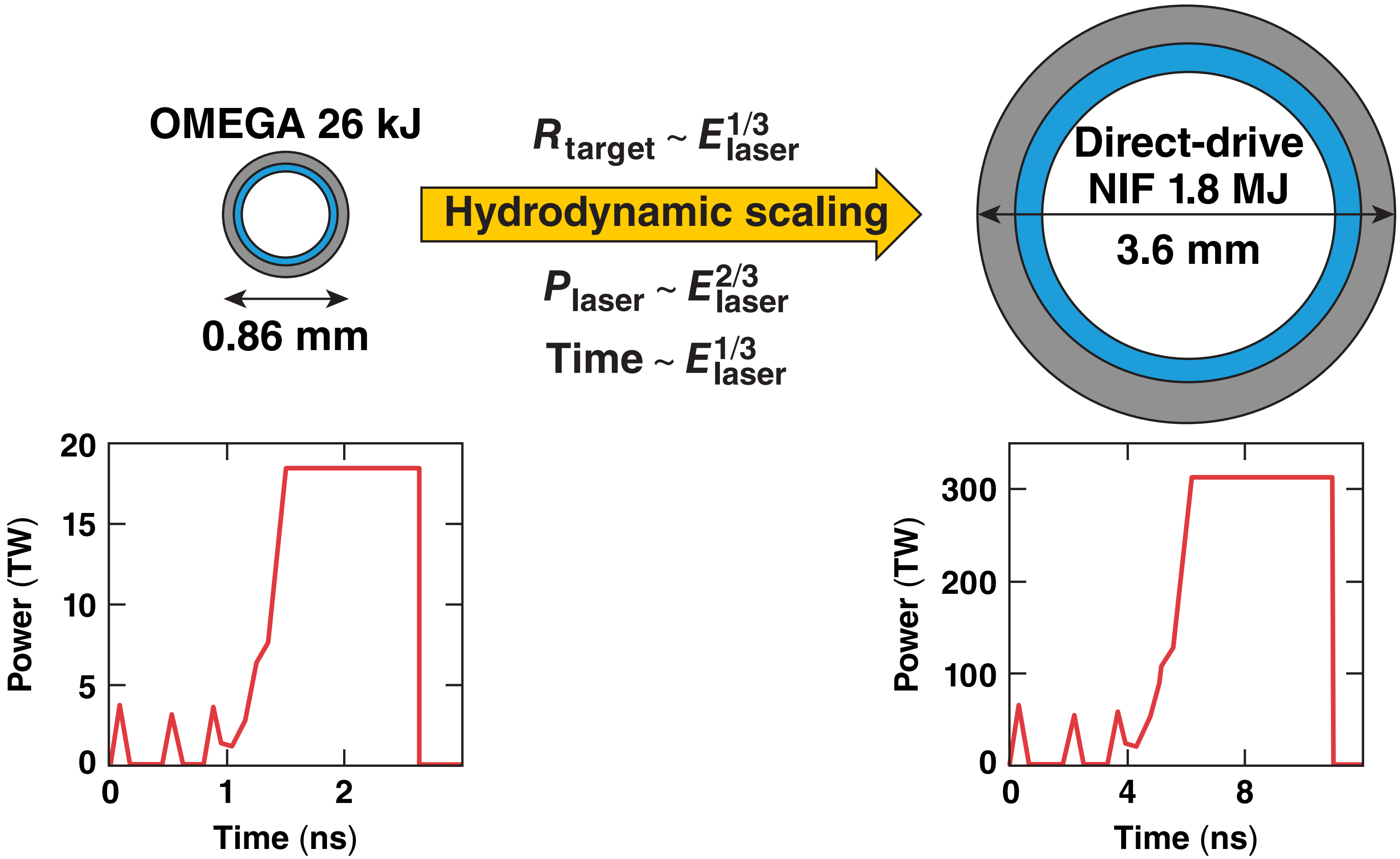
- Expect improvement in relative nonuniformities on the NIF as a result of larger hot-spot size, more beams, and equal ice roughness

Energy scaling ⟶

$$\chi_{\mathrm{NIF}} \approx \chi_{\Omega}\left(V_{\mathrm{i}}, \alpha, I_{\mathrm{laser}}\right) 2^{0.34}\left(\frac{E_{\mathrm{laser}}^{\mathrm{NIF}}}{E_{\mathrm{laser}}^{\Omega}}\right)^{0.4}$$

$$\mathrm{ITFx}_{\mathrm{NIF}} \approx 2 \times \mathrm{ITFx}_{\Omega} \times \left(\frac{E_{\mathrm{laser}}^{\mathrm{NIF}}}{E_{\mathrm{laser}}^{\Omega}}\right)^{1.28}$$

Targets and laser pulses are designed for OMEGA to reproduce direct-drive NIF hydrodynamics



TC10267b

Hydro-equivalent ignition at 26 kJ on OMEGA requires an ~1.7× improvement in areal density and ~2× improvement in neutron yield

- χ = 0.16 is required for hydro-equivalent ignition on OMEGA

$$\chi \approx \left(\rho R^{\text{no}\,\alpha}_{\text{g/cm}^2}\right)^{0.61} \left(\frac{0.24\, Y_n^{16}}{M_{DT}^{mg}}\right)^{0.34}$$

- ρR is the areal density, Y_n is the neutron yield, and M_{DT} is the DT fuel mass
- Current OMEGA experiments: M_{DT} = 0.02 mg, $\rho R \approx 0.18$ g/cm^2, $Y_n \approx 2 \times 10^{13} \rightarrow \chi = 0.09$
- Required for hydro-equivalent ignition: M_{DT} = 0.02 mg, $\rho R \approx 0.3$ g/cm^2, $Y_n \approx 4 \times 10^{13} \rightarrow \chi = 0.17$

OMEGA performance can be scaled up to NIF energies and spherically symmetric drive. The extrapolated ITFx for direct drive on NIF is about 0.18 → $\chi \approx 0.56$

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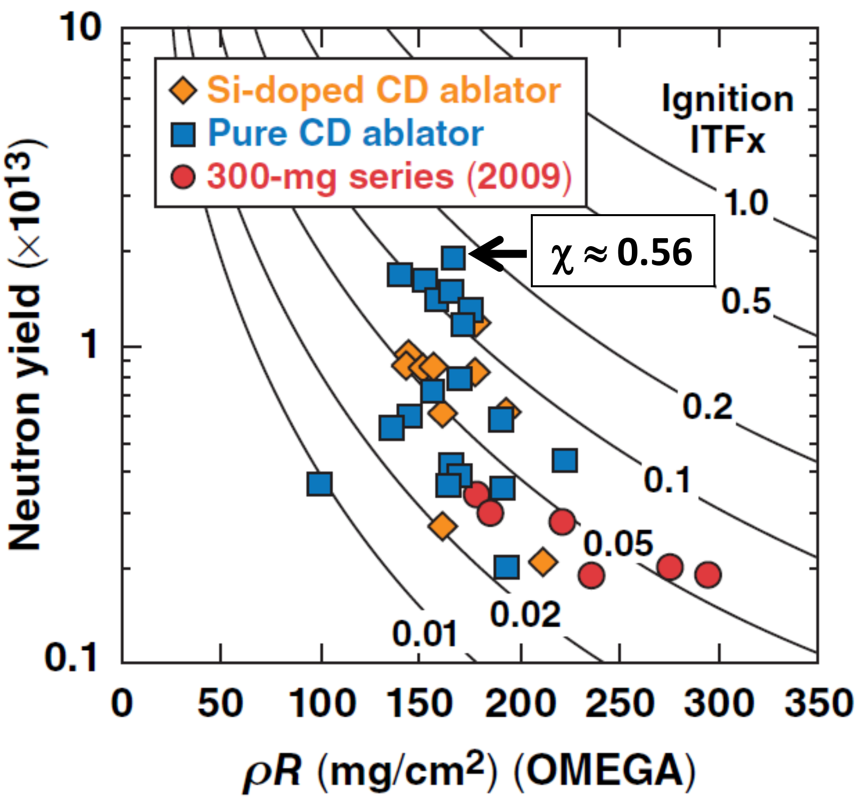
ITFx on the NIF for scaled up (1.8-MJ) OMEGA results (with large uncertainties)



- This is a purely hydrodynamic scaling
- It does not include laser–plasma instability effects
- It does not include the polar-drive configuration of the NIF
- Given the large extrapolation and limited physics, this result should be considered as a rough estimate

*T. C. Sangster *et al.*, "Improving Cryogenic DT Implosion Performance on OMEGA," to be published in Physics of Plasmas.

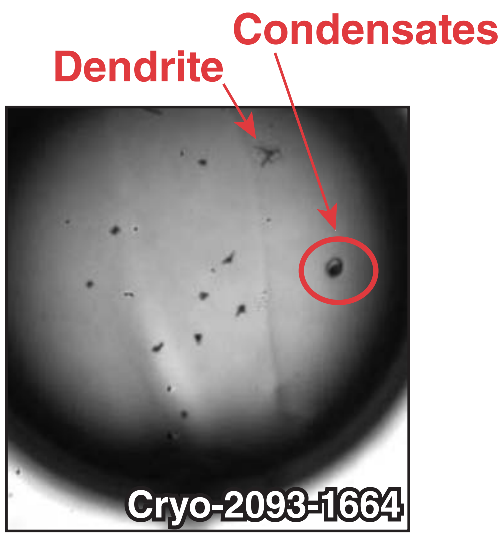
TC10124e

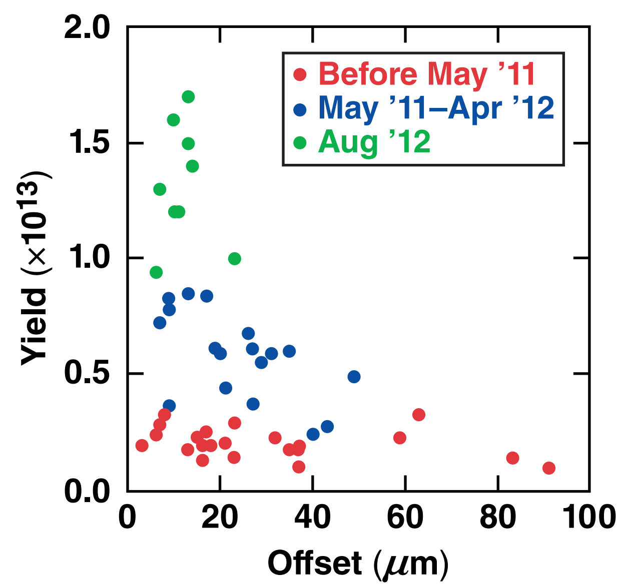
What is limiting the performance of OMEGA implosions?

Isolated defects on the shell surface of cryogenic DT targets severely limits the implosion performance

- Isolated surface debris on the target appear to be limiting the implosion performance
  - a significant engineering effort is underway to remove the defects
  - a 2011 shot series showed improved yields when fewer defects were present

Cryo target image





TC10132b

The Tritium Fill System hydrogen permeator will remove all non-hydrogen contaminants in the LLE DT fuel supply

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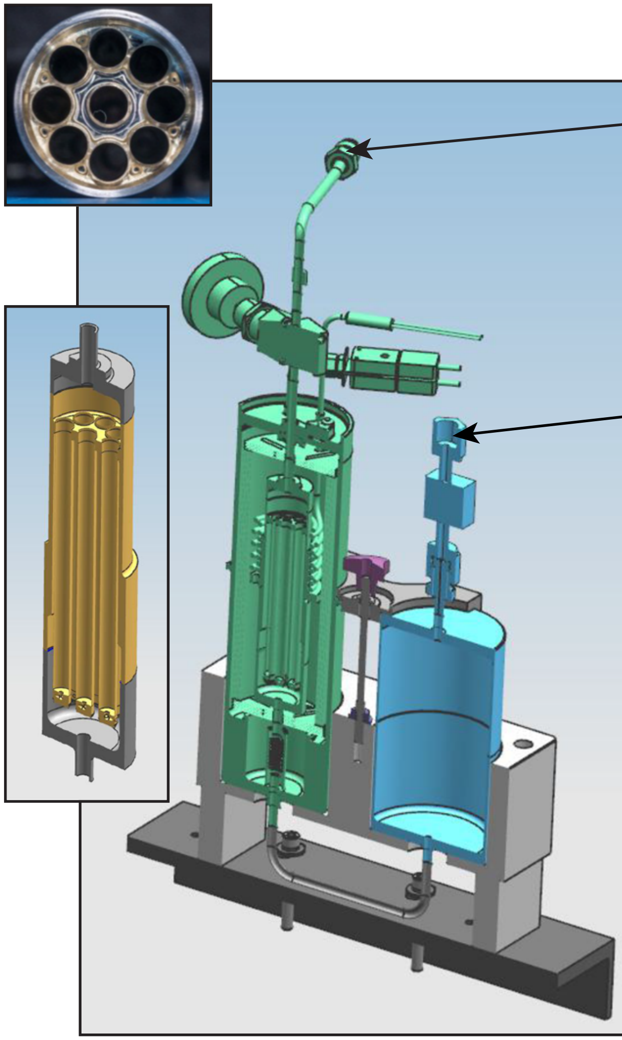
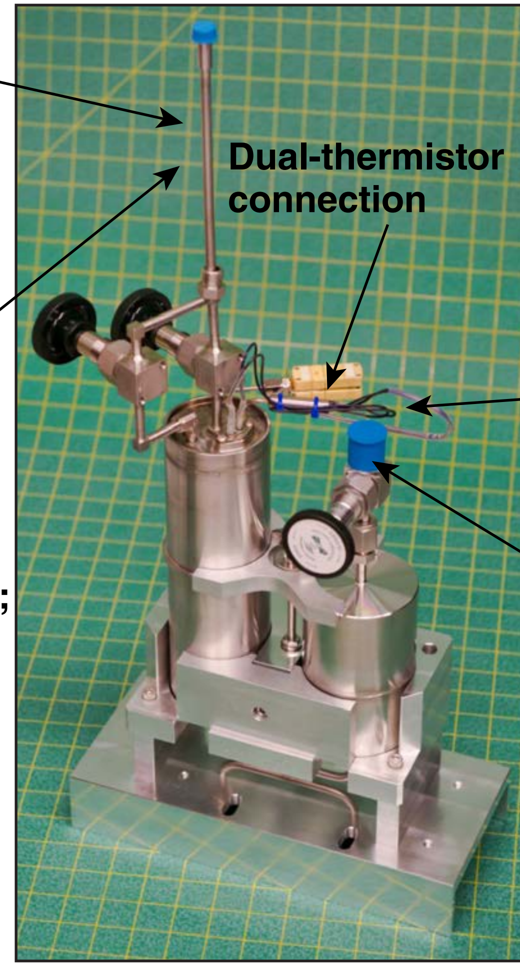




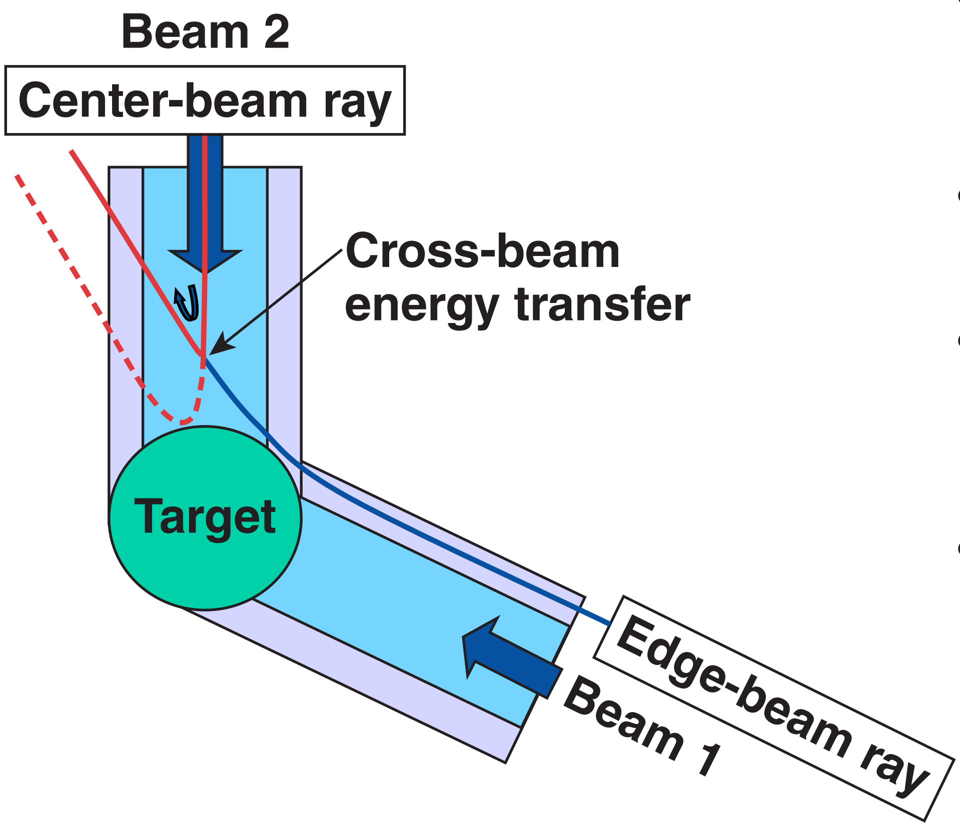
No automated interlocks; all manual valves

No interlocks to prevent hydration of membrane

First use will be for 19 February cryo targets.

The performance of direct-drive capsules is further degraded by cross-beam energy transfer (CBET)

UR LLE



- CBET involves electromagnetic (EM)-seeded, low-gain stimulated Brillouin scattering
- EM seed is provided by edge-beam light
- Center-beam light transfers some of its energy to outgoing light*
- The transferred light bypasses the highest absorption region near the critical surface*

CBET reduces laser absorption and hydrodynamic efficiency.**

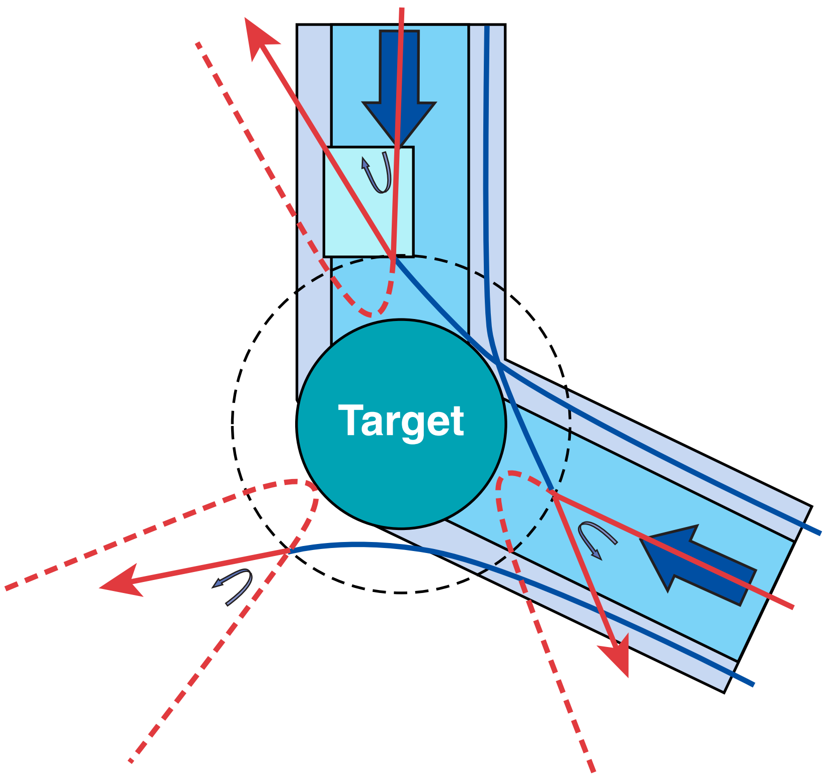
E19905t

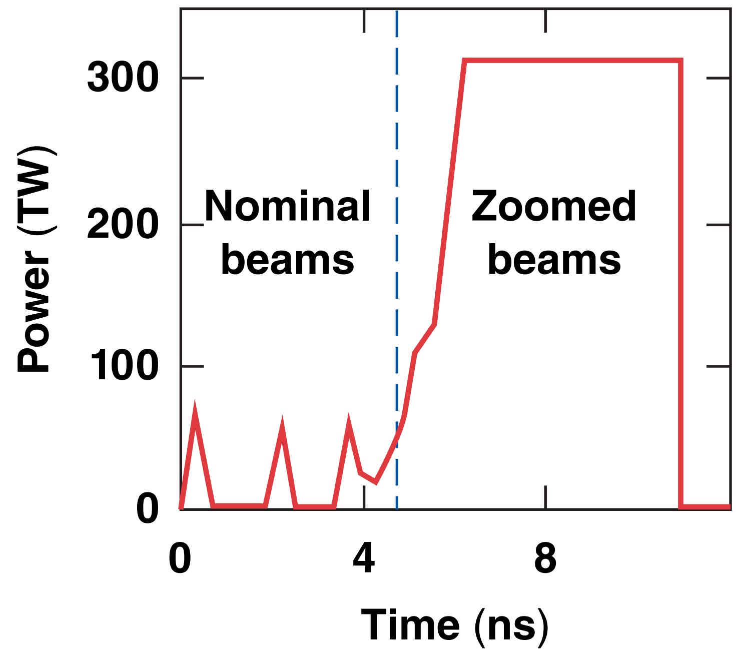
* D. H. Edgell *et al*., Bull. Am. Phys. Soc. 52, 195 (2007); 53, 168 (2008); 54, 145 (2009).

** I. V. Igumenshchev *et al*., Phys. Plasmas 17, 122708 (2010).

Several options to mitigate the effects of CBET are currently under investigation

- **Two-state laser beam zooming**





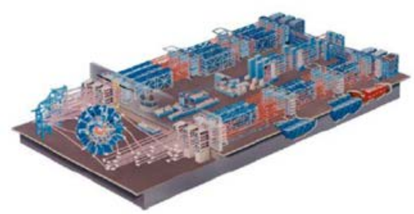
- **Other possible solutions**
  - **stacked laser pulse: 96 beams with large focal spot $R_{beam} = R_{target}$ followed by 96 beams zoomed at $R_{beam} = 0.5\ R_{target}$**
  - **moderate-*Z* ablators like carbon or saran (CHCl) or glass**

I2101

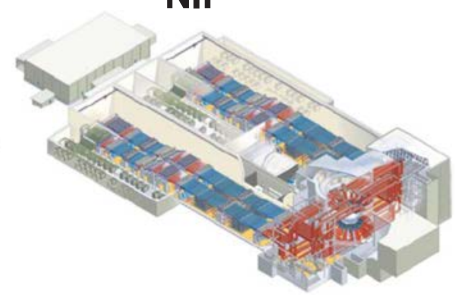
Demonstrating hydro-equivalent ignition on OMEGA is a major step forward but does not resolve all the uncertainties about achieving ignition on the NIF

Non-hydrodynamic physics that does not scale

OMEGA



NIF



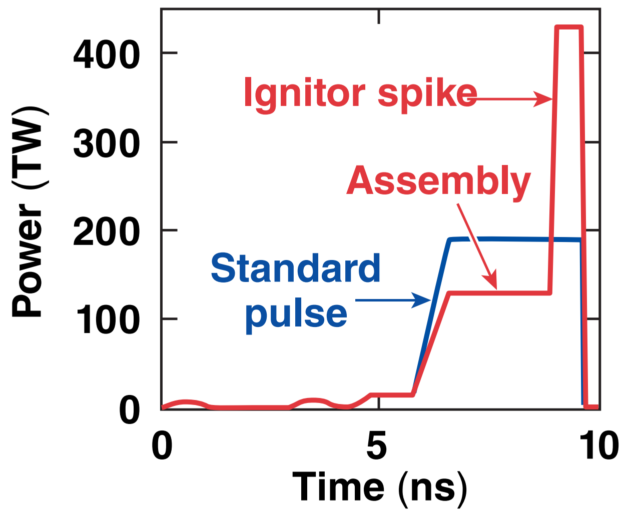
Laser-energy collisional absorption	Less	Better →	More
Laser–plasma instabilities and hot-electron preheat	Less	Worse →	More
Cross-beam energy transfer	Less	Worse →	More
Radiation preheat	More	Better →	Less

Alternate direct-drive–ignition schemes

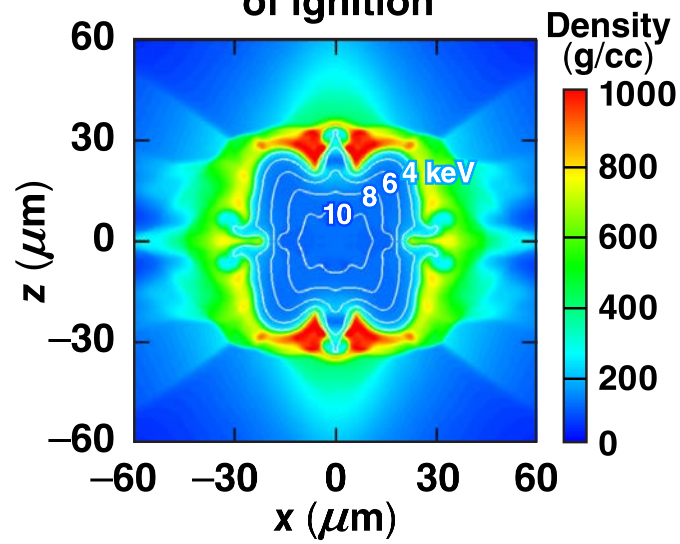
Shock ignition is a promising alternative to conventional direct-drive implosions

UR LLE

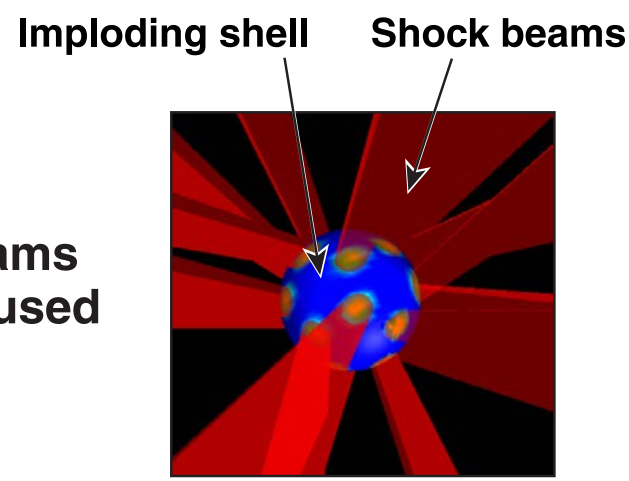
Shock ignition versus conventional direct-drive laser pulses



Density at onset of ignition



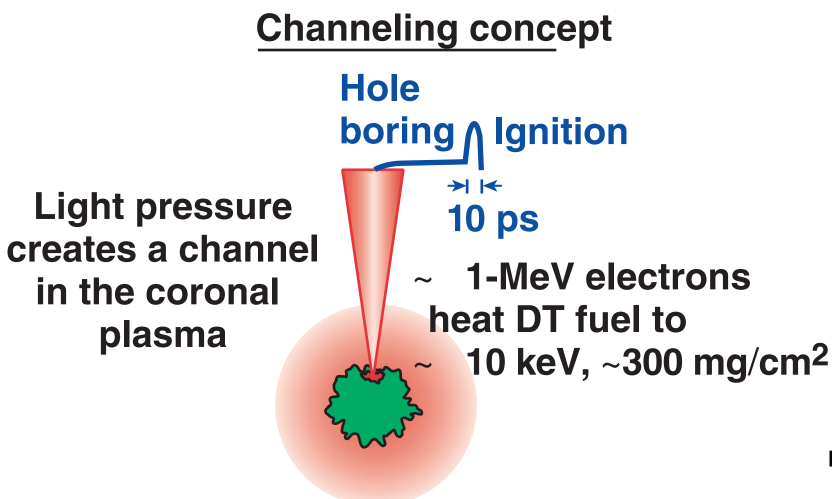
The shock beams are tightly focused on target

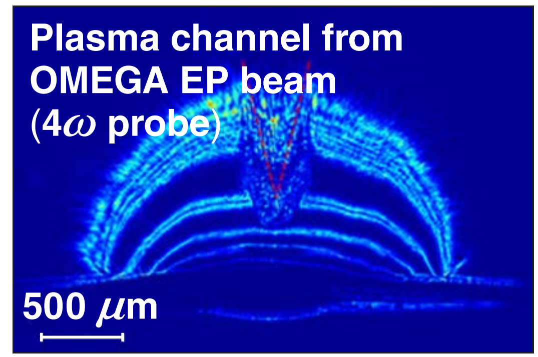


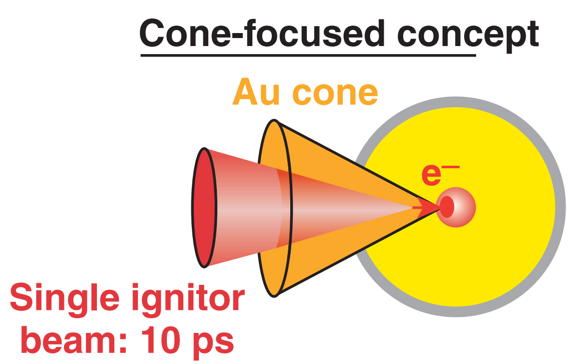
2-D simulations of the shock-ignition target designs for the NIF in polar drive predict ignition with Gain = 52 at 750 kJ of laser energy (no CBET included)

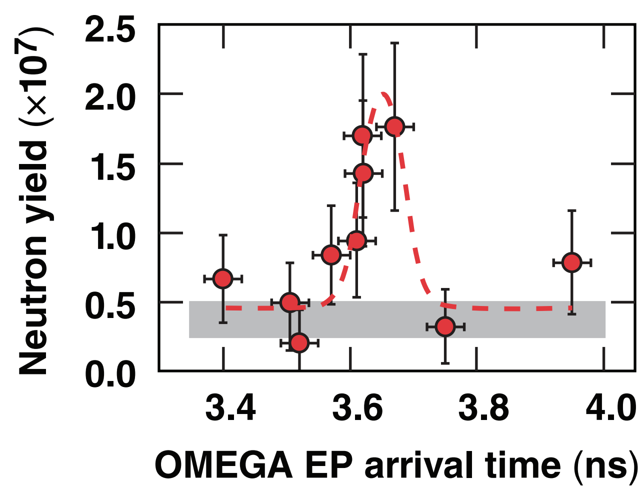
I2104

Research in high-intensity laser–plasma interaction provides the basis for fusion applications of high-power lasers (fast ignition)









Summary/Conclusions

Steady progress continues to be made in direct-drive ignition; ignition-scalable performance on OMEGA is within reach

- Current cryogenic implosions on the OMEGA laser do not yet scale to ignition on the NIF
- Hydro-equivalent ignition on OMEGA requires improvements in areal density (~1.7×) and neutron yields (~2×)
- Causes for implosion-performance degradation have been identified (isolated defects and cross-beam energy transfer) and are being addressed
- Shock ignition is a promising path to direct-drive ignition and ignition designs for the NIF have been developed and simulated
- High-power lasers provide additional ignition options (fast ignition)