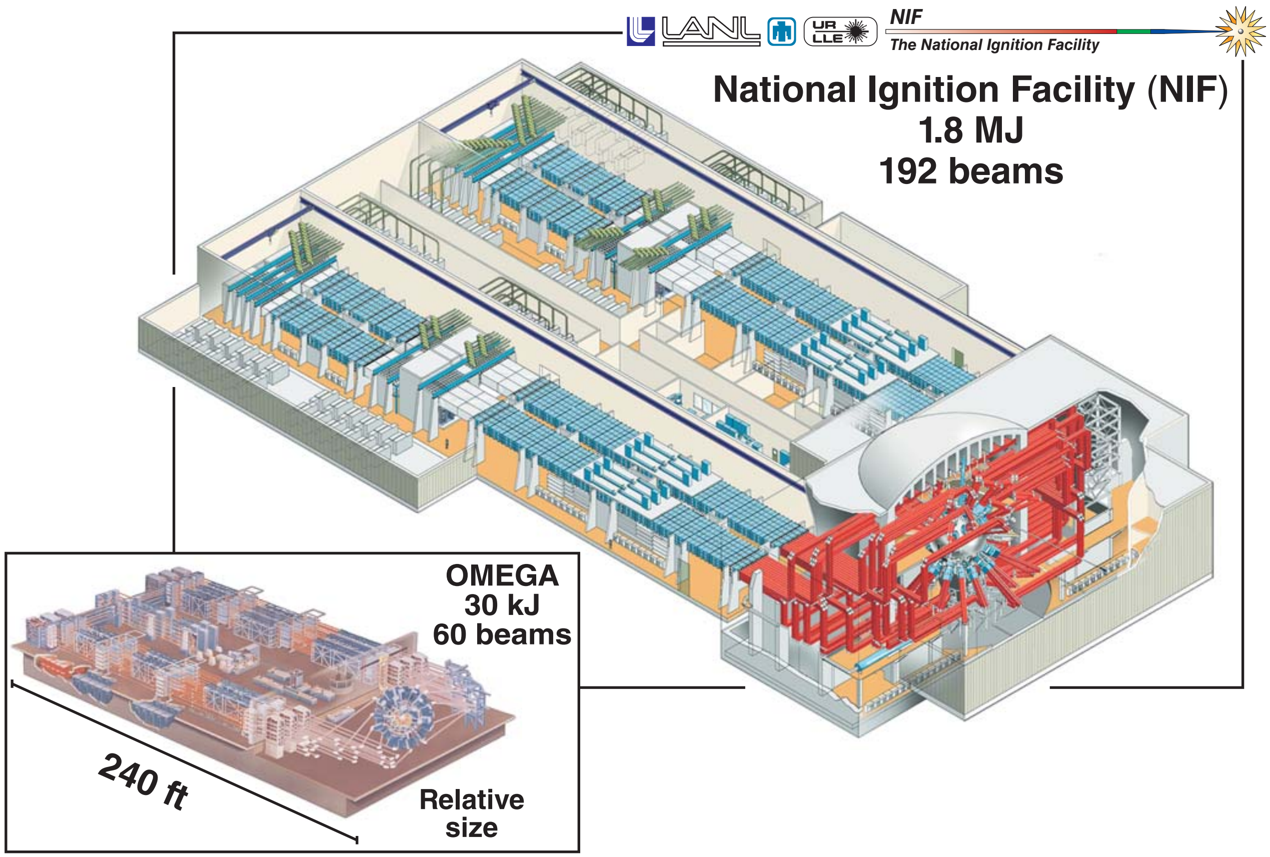
Direct-Drive Inertial Confinement Fusion Research at the Laboratory for Laser Energetics: Charting the Path to Thermonuclear Ignition



R. L. McCrory, S. P. Regan
University of Rochester
Laboratory for Laser Energetics

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Collaborators

S. J. Loucks, D. D. Meyerhofer, S. Skupsky, R. Betti, T. R. Boehly, R. S. Craxton, T. J. B. Collins, J. A. Delettrez, D. Edgell, R. Epstein, V. Yu. Glebov, V. N. Goncharov, D. R. Harding, R. L. Keck, J. P. Knauer, J. Marciante, J. A. Marozas, F. J. Marshall, A. Maximov, P. W. McKenty, J. Myatt, P. B. Radha, T. C. Sangster, W. Seka, V. A. Smalyuk, J. M. Soures, C. Stoeckl, B. Yaakobi, and J. D. Zuegel

Laboratory for Laser Energetics, University of Rochester
250 East River Road, Rochester, NY 14623-1299

C. K. Li, R. D. Petrasso, F. H. Séguin, and J. A. Frenje

Plasma Science and Fusion Center, MIT
Boston, MA, USA

S. Paladino, C. Freeman, and K. Fletcher

State University of New York at Geneseo
Geneseo, NY, USA

Summary

Significant theoretical and experimental progress continues to be made at LLE – charting the path to ignition with direct-drive ICF

UR LLE

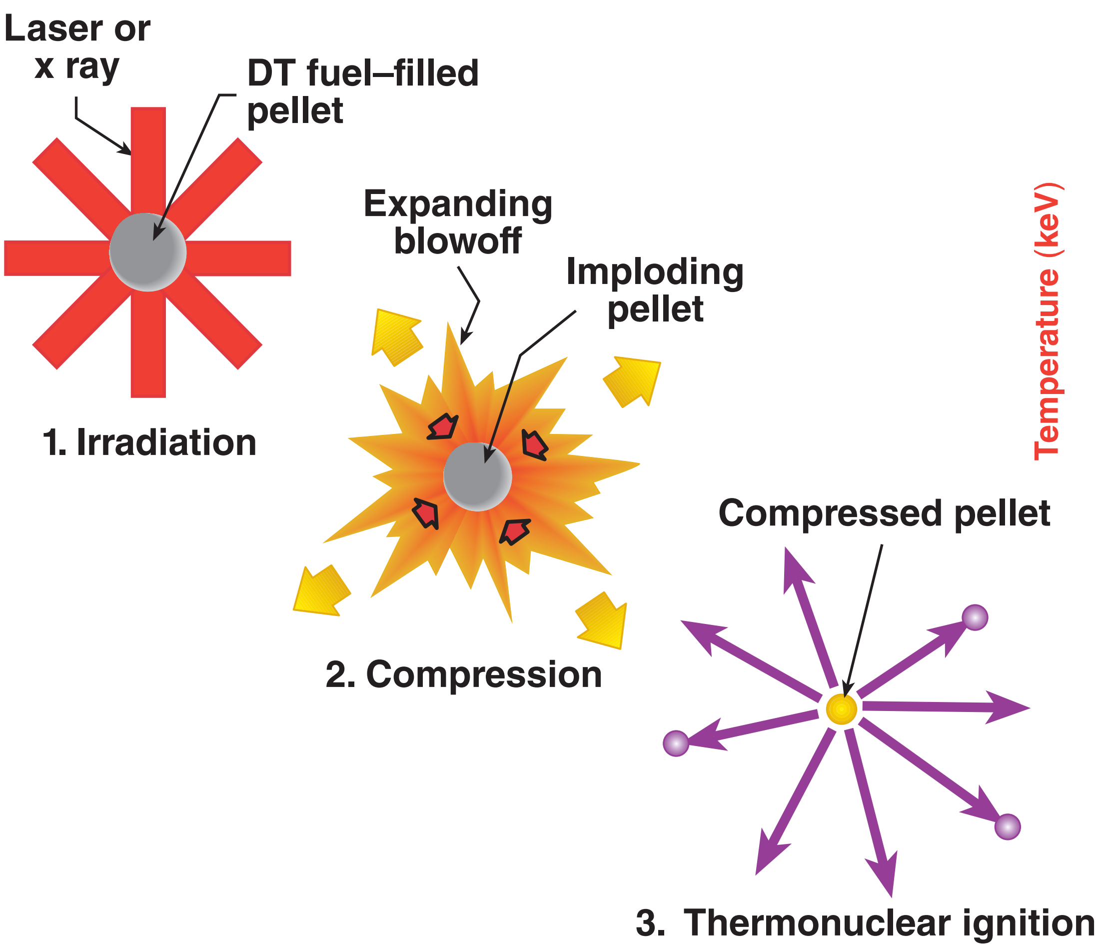
- Ignition target designs are being validated on OMEGA with scaled implosions of cryogenic D2/DT targets.
- Symmetric direct drive on the National Ignition Facility (NIF) is predicted to achieve high-gain (~40).
- Direct drive targets are predicted to ignite on the NIF while it is in x-ray-drive configuration with polar direct drive (PDD).
- Fully integrated fast-ignition (FI) experiments will begin on OMEGA with the completion of the high energy petawatt (HEPW) upgrade – OMEGA EP.

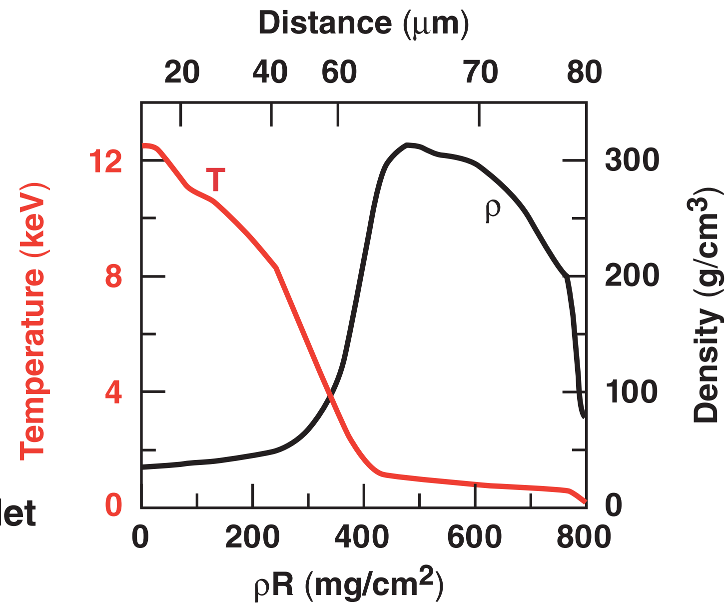
Prospects for thermonuclear ignition with direct drive on the NIF are extremely promising.

Outline

- Direct-drive inertial confinement fusion (ICF)
- OMEGA
- Symmetric illumination direct-drive ignition designs
- Polar direct drive
- Fast ignition research

Ablation is used to generate the extreme pressures required to compress a fusion capsule to ignition conditions





"Hot-spot" ignition requires the core temperature to be at least 10 keV and the core fuel areal density to exceed ~300 mg/cm^2.

The OMEGA laser is the most powerful UV laser for fusion research in the world

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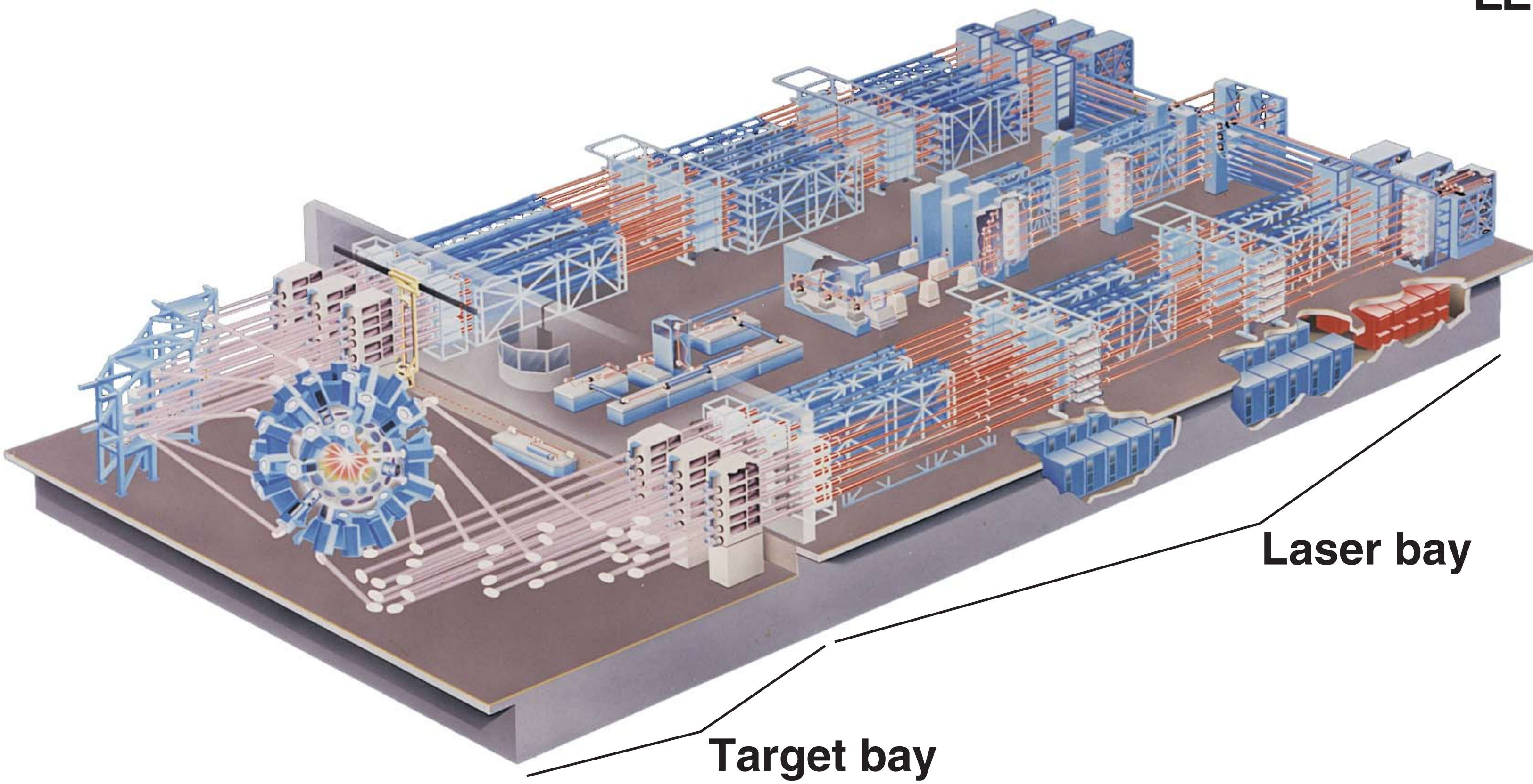
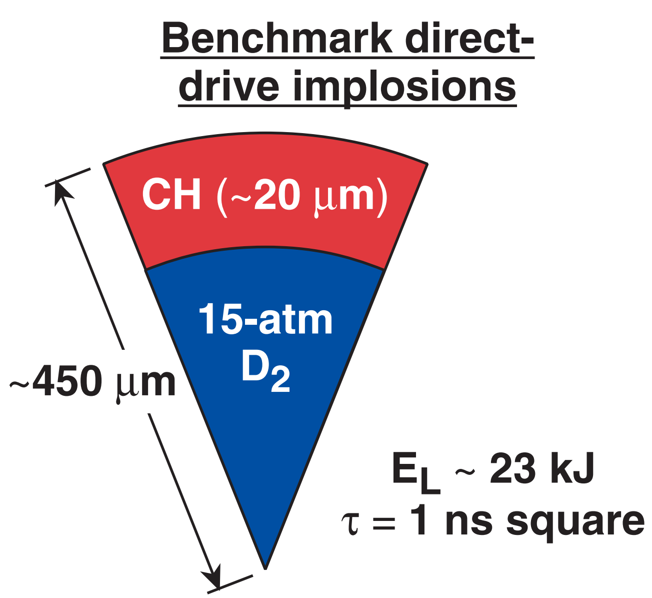
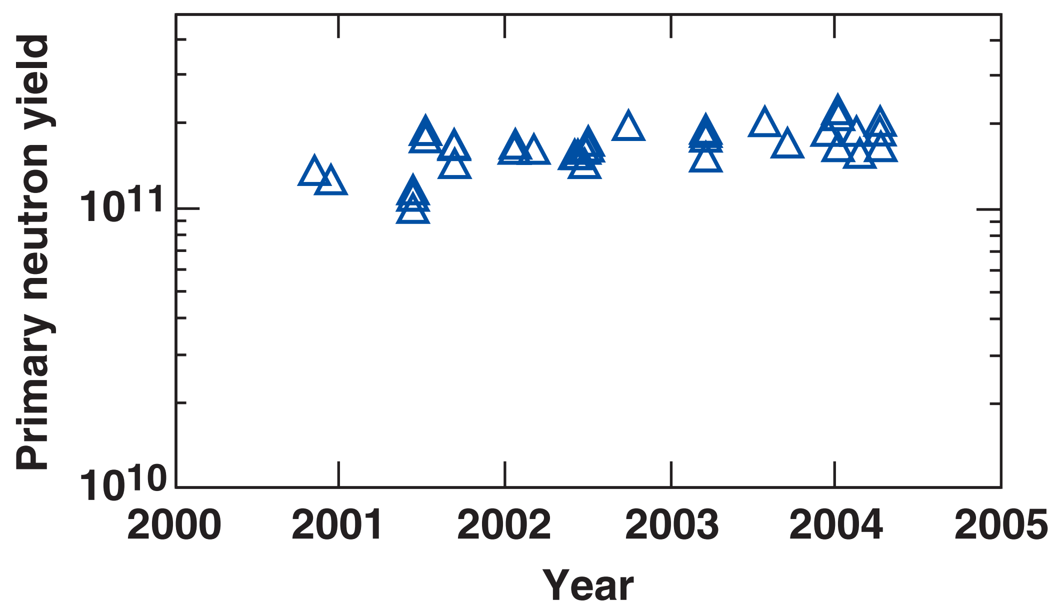


- 60 beams
- >30 kJ UV on target
- 1%–2% irradiation nonuniformity
- Flexible pulse shaping
- Short shot cycle (1 h)

TC2998w

OMEGA creates extreme states of matter with high reproducibility

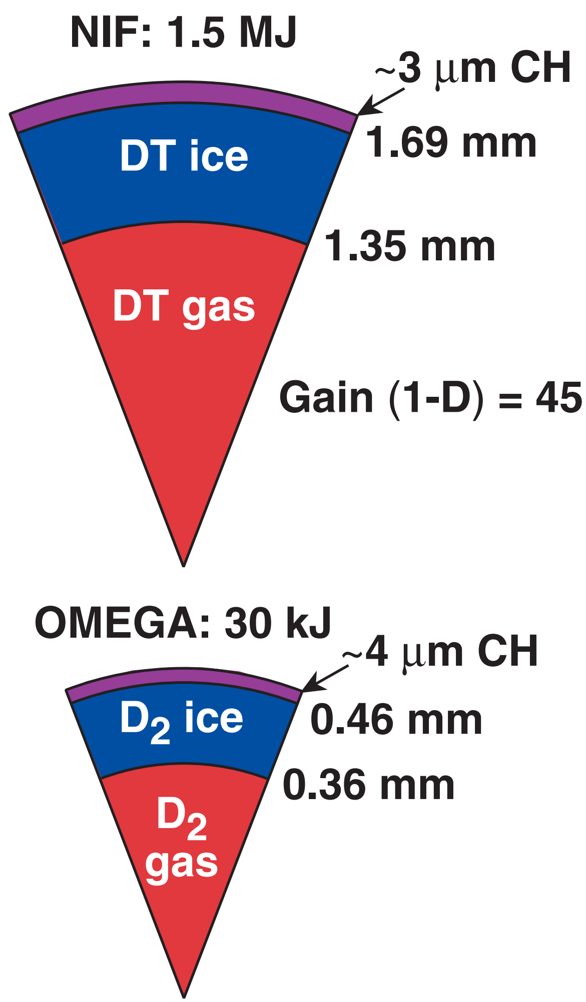




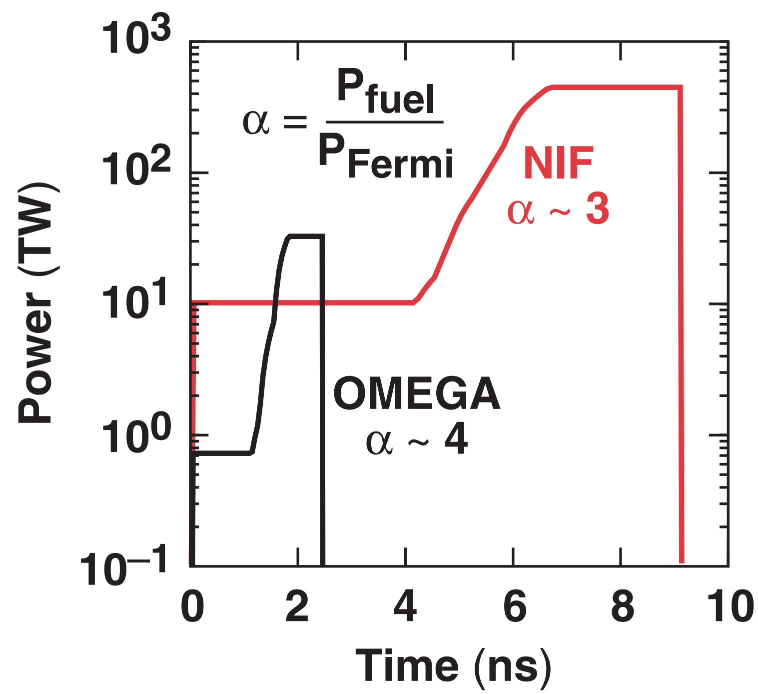
- Compressed pressures of 5~10 Gbar
- DT neutron yields of 10^{14}
- Peak ion temperatures of ~20 keV

I1517b

OMEGA cryogenic targets are energy scaled from the NIF symmetric direct-drive point design



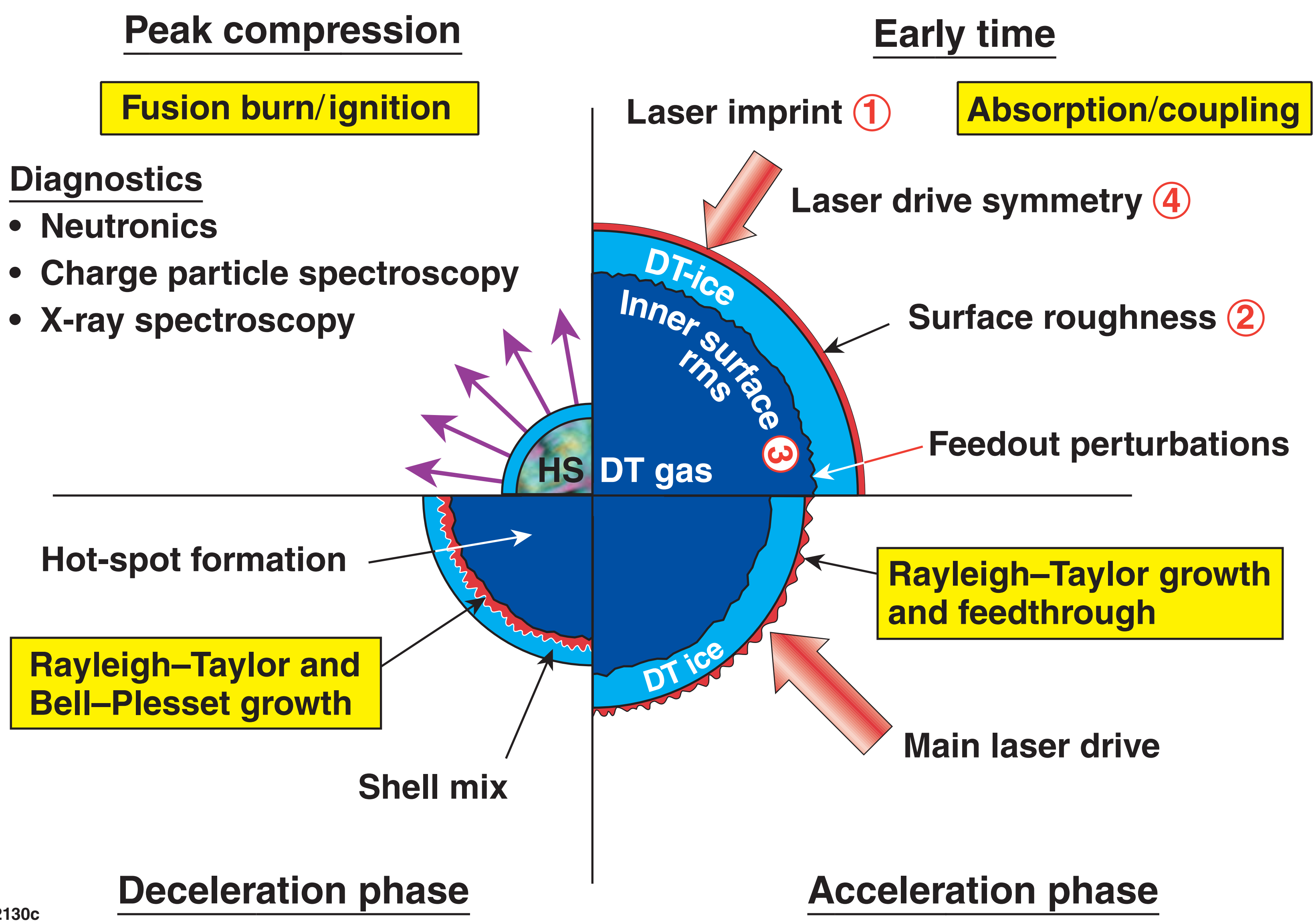
Energy ~ radius^3;
power ~ radius^2;
time ~ radius



Initial cryogenic DT implosions are expected in spring 2005.

E11251j

Perturbation seeds from four sources early in the implosion determine the final capsule performance



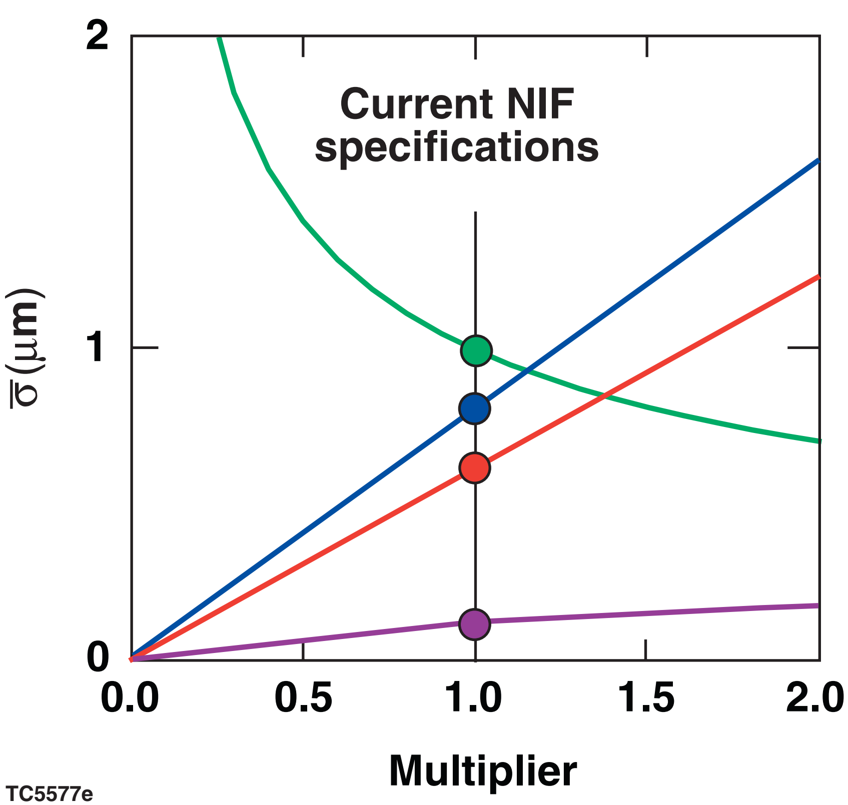
E12130c

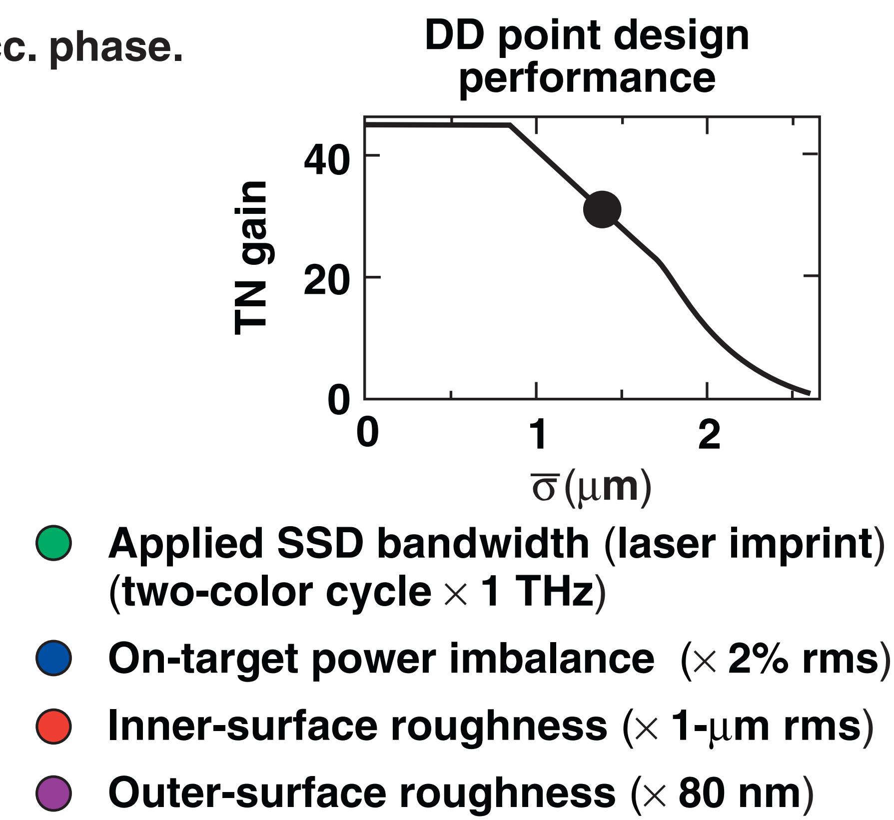
A global nonuniformity budget for the direct-drive point design can be formed by scaling gain with $\overline{\sigma}$

- **The NIF gain* and OMEGA yield can be related by**

$$\overline{\sigma}^2 = 0.06\,\sigma^2_{\ell<10} + \sigma^2_{\ell\geq 10};$$

σ_ℓ = rms amplitudes at the end of the acc. phase.





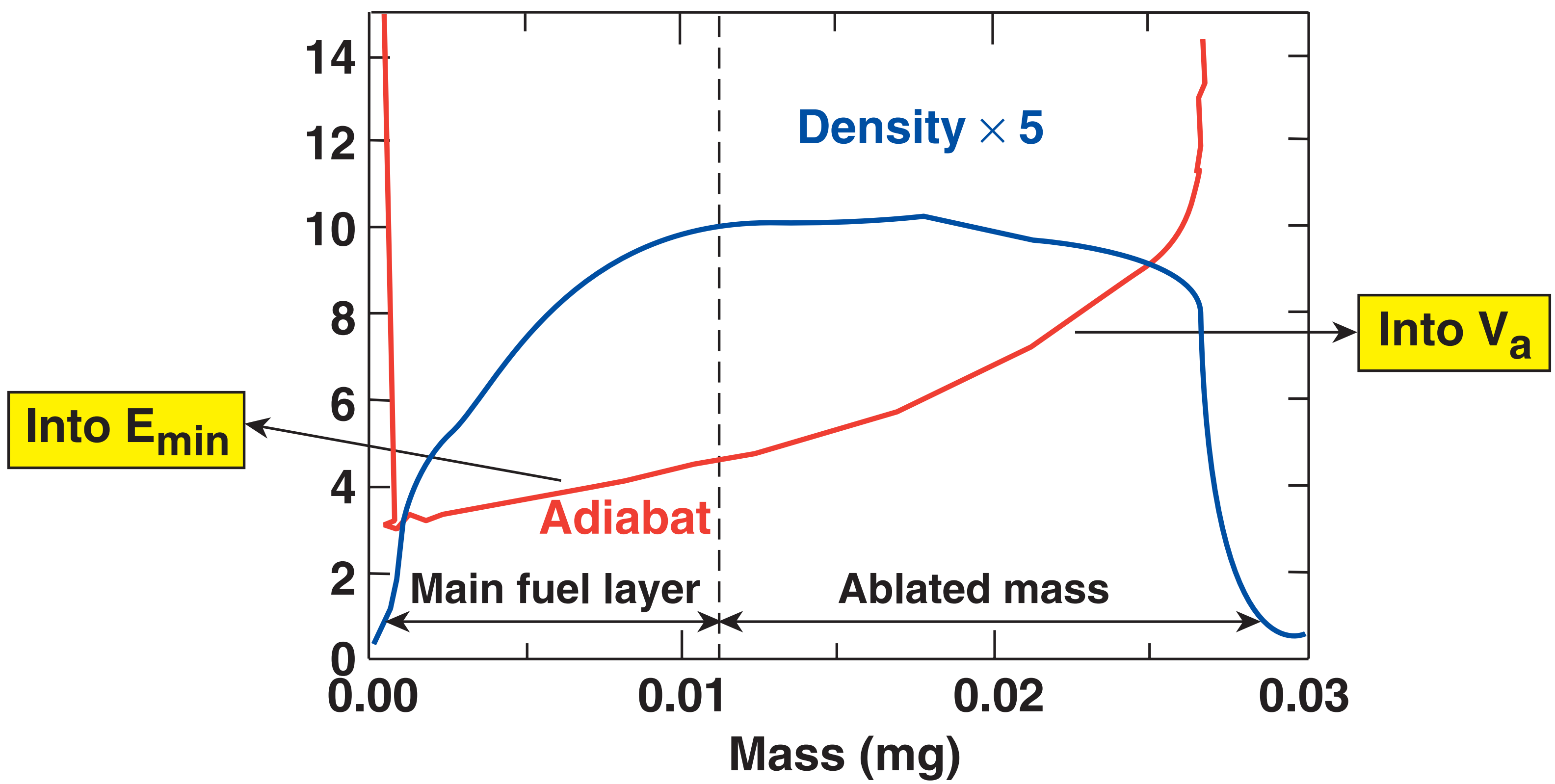
TC5577e

* P. McKenty *et al.*, Phys. Plasmas 8, 2315 (2001).

Laser imprint

Shell stability and compressibility depend on the adiabat

- Mimimum energy required for ignition:[1,2] $E_{min} \sim \alpha^{1.88}$ $\alpha = P/P_{Fermi}$
- Rayleigh–Taylor instability growth $\gamma = \alpha_{RT}(kg)^{1/2} - \beta_{RT}kV_a$ $V_a \sim \alpha^{3/5}$

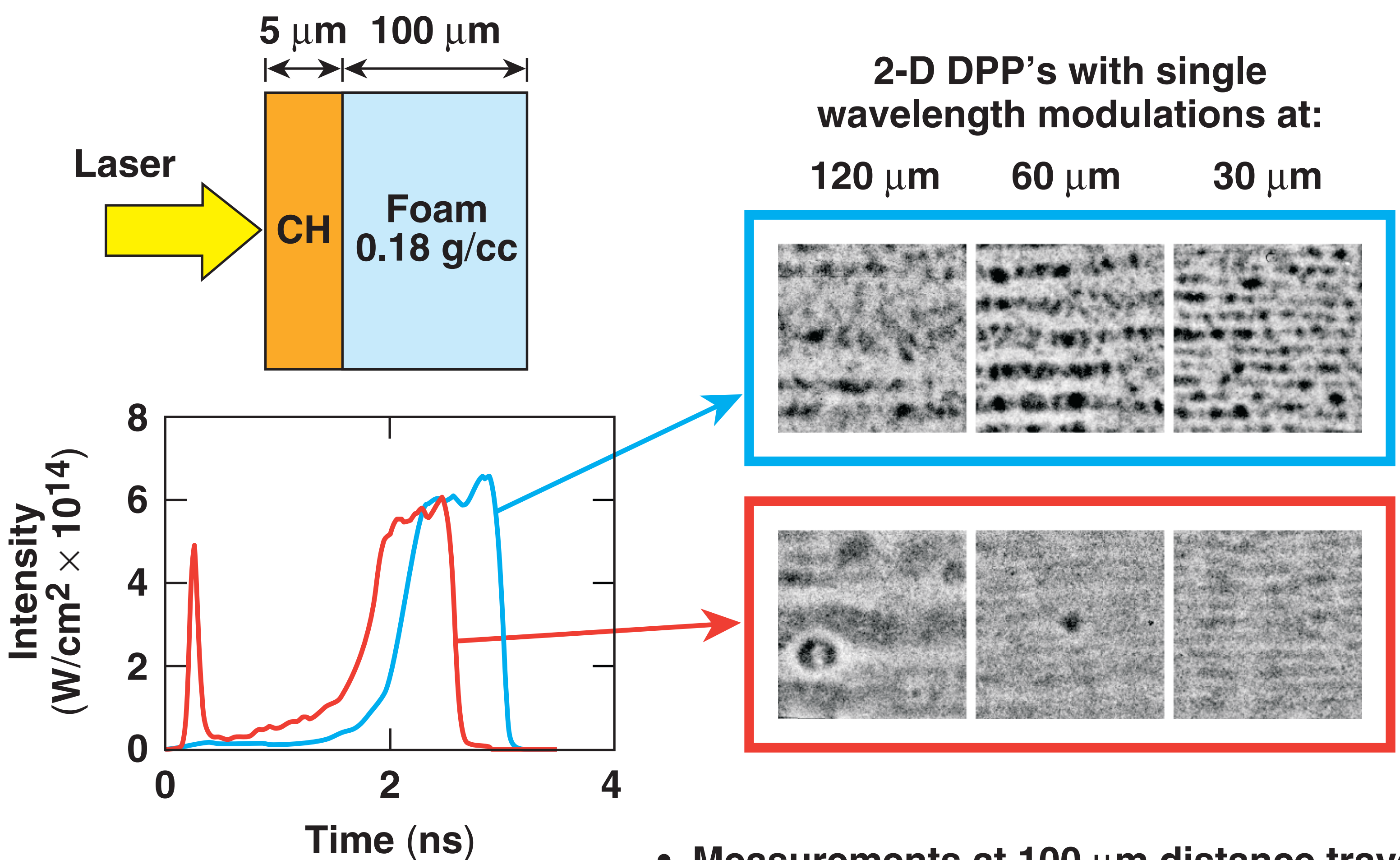


Adiabat shaping is achieved using a high intensity picket laser pulse.

TC5950c

[1]M. Herrmann et al., Phys. Plasmas 8, 2296 (2001).
[2]R. Betti et al., Phys. Plasmas 9, 2277 (2000).

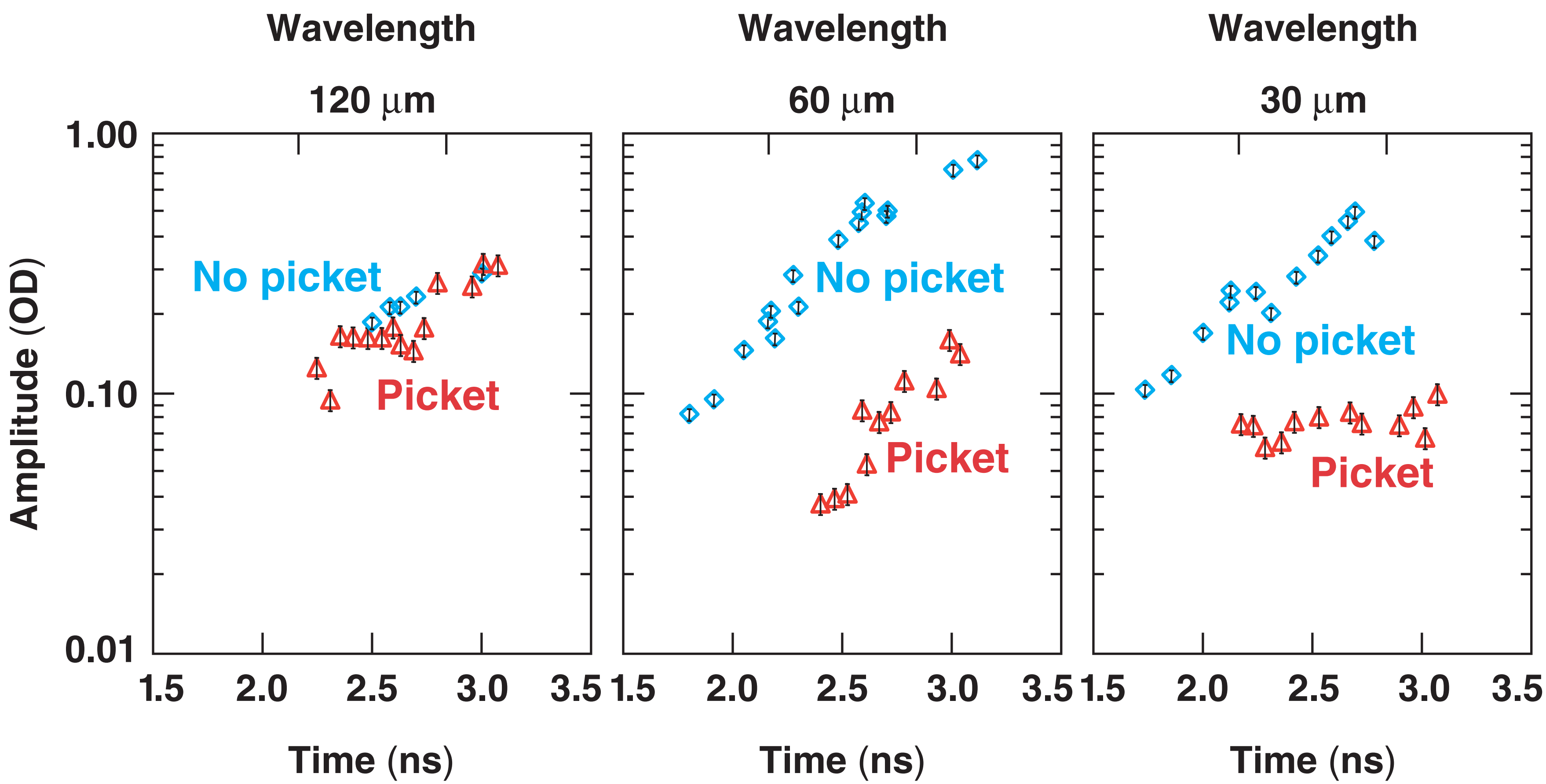
Measured radiographs show significant imprint reduction with picket pulses



- Measurements at 100 μm distance traveled.

V. N. Goncharov, Phys. Plasmas 10, 1906 (2003).

Optical-depth modulations are significantly reduced at shorter wavelengths using a picket pulse



E12855b

Adiabat shaping is a very powerful technique to reduce the growth of hydrodynamic instabilities

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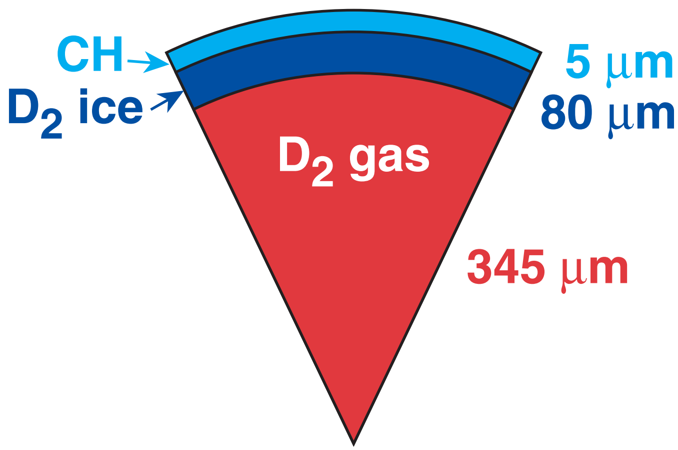
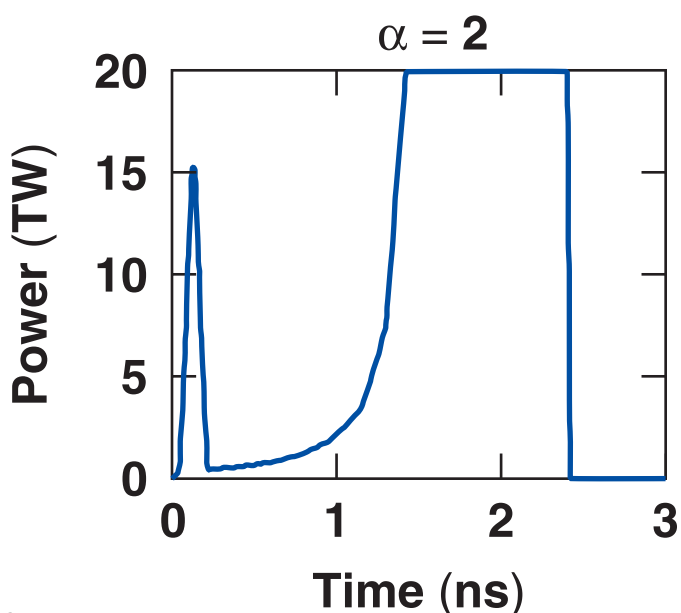
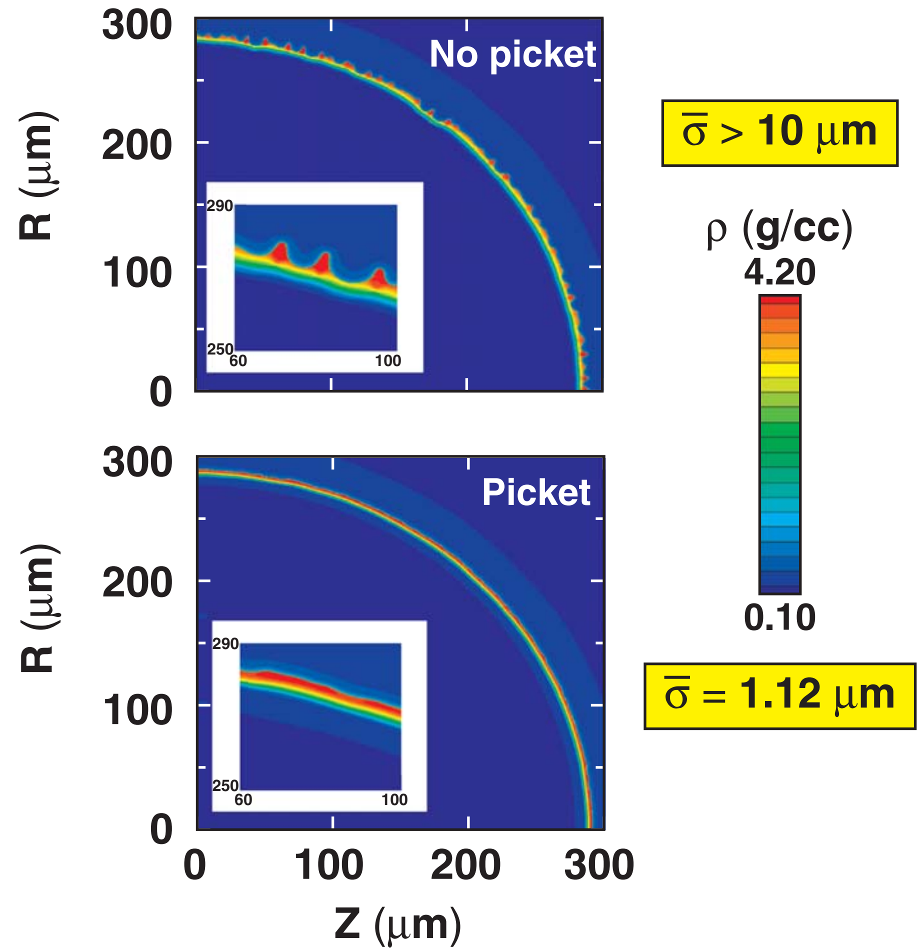




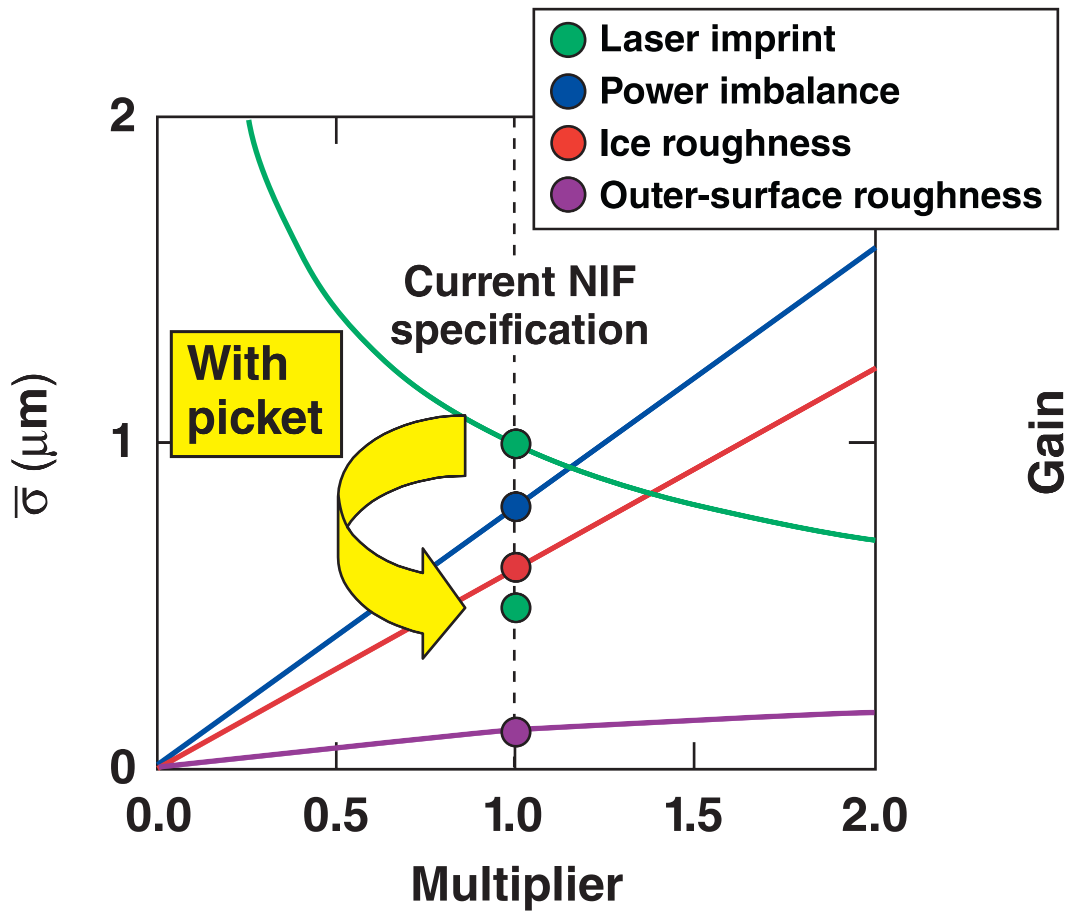
Imprint simulations

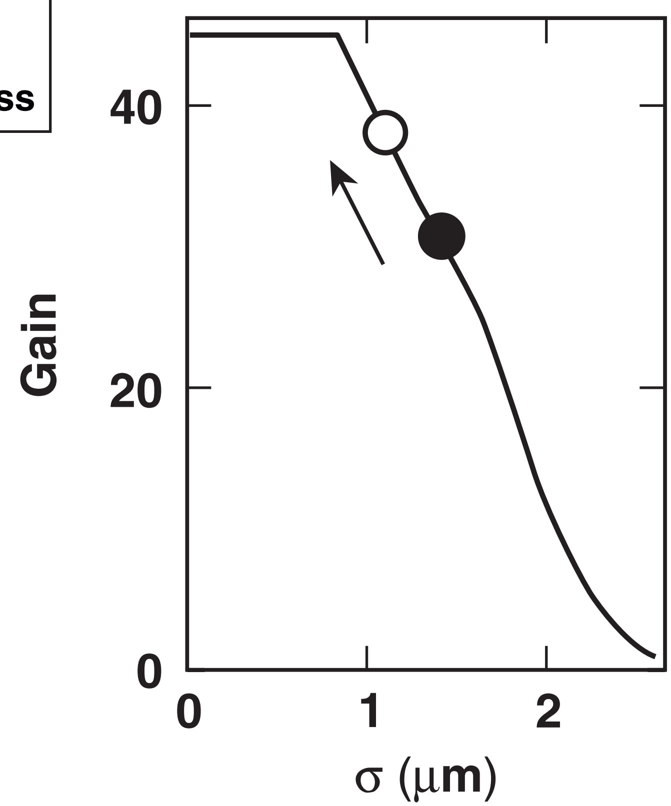
ORCHID: ℓ = 2–200, DPP + PS, 1-THz SSD



TC6341b

Direct-drive target stability is dramatically improved when adiabat shaping is applied





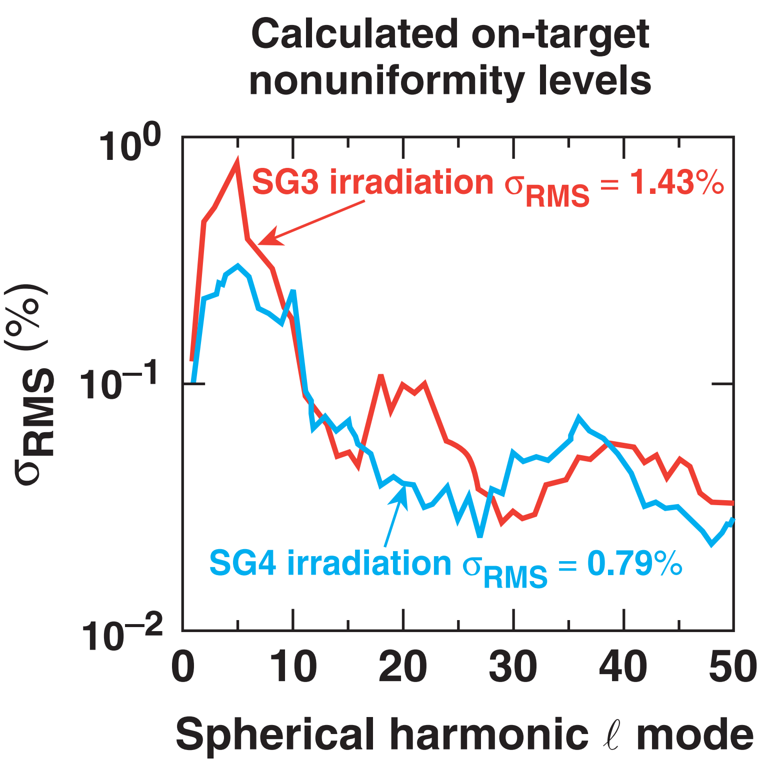
The benefit of pickets has been confirmed in NRL and LLNL simulations.

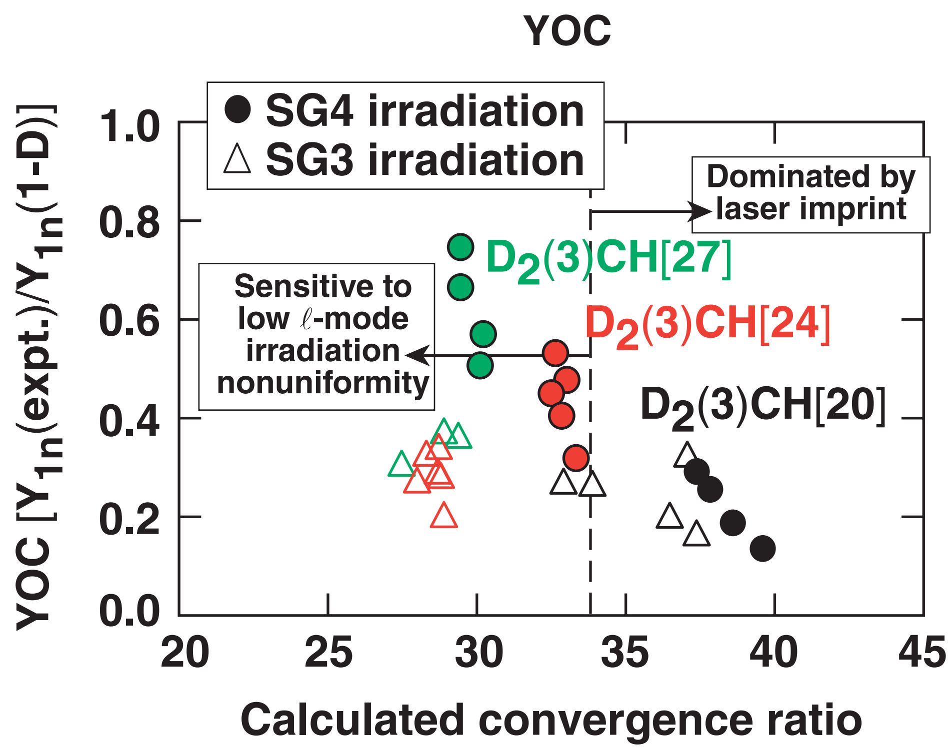
TC6339d

Power Imbalance

Reduction of the on-target laser irradiation nonuniformity on OMEGA dramatically improved implosion performance

- Far field intensity envelope: $I(r) \propto \exp\left[-\left(\frac{r}{\delta}\right)^n\right]$
- New phase plate design n = 4.1 (SG4)
- Old phase plate design n = 2.2 (SG3)



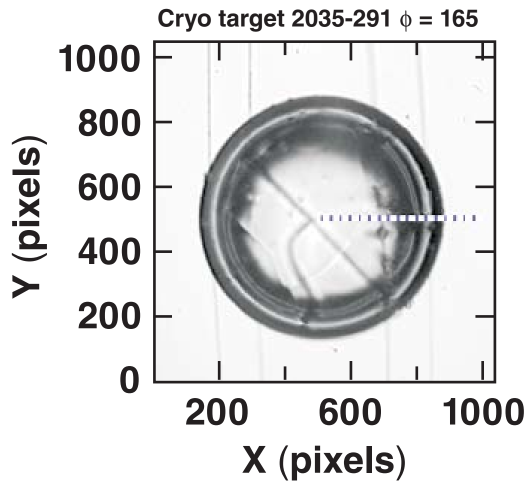


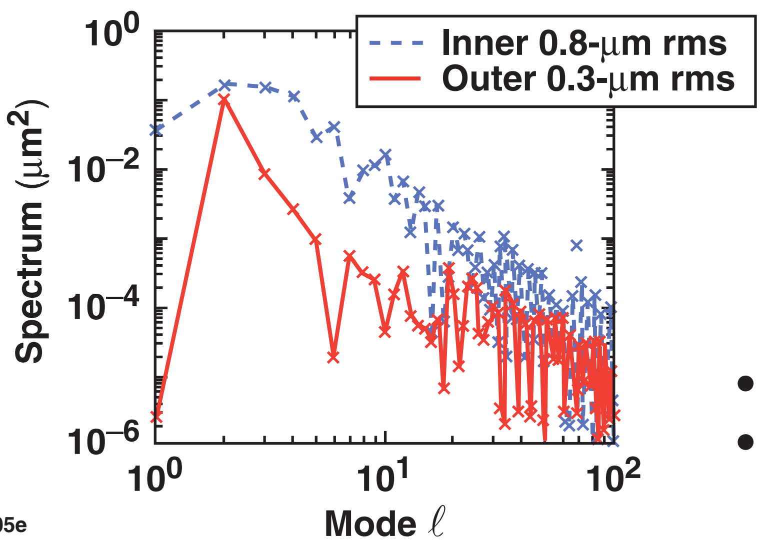
I1566

Ice Roughness

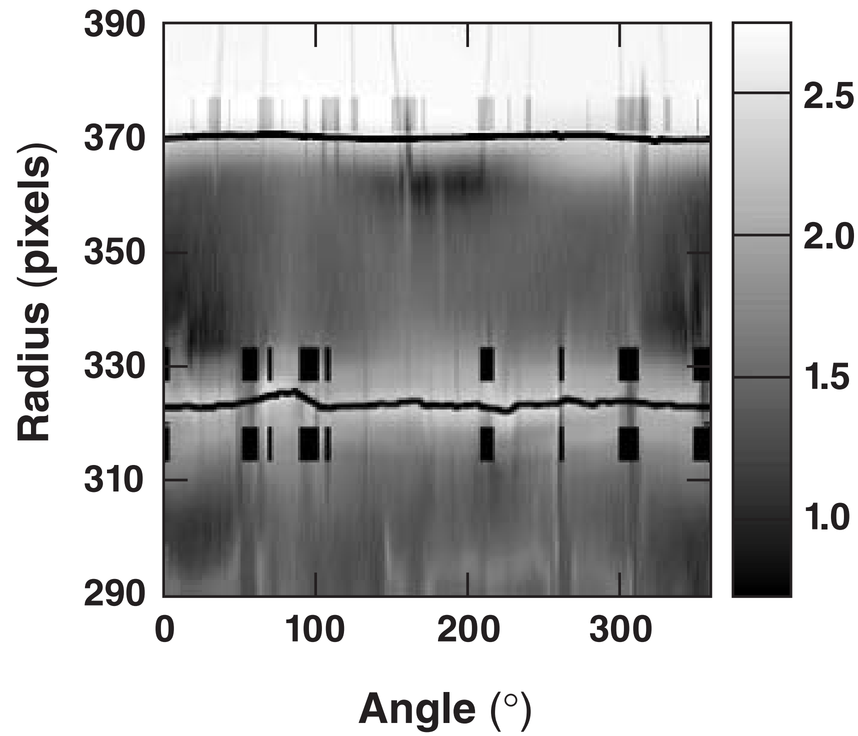
Submicron rms ice layers were demonstrated; the smoothest layers were confined to localized regions of the target

Shadowgraph of layered cryogenic target





Unwrapped Image



- 24 views every 15° in "x" and "y"
- 0.8 to 1.4 μm over 1/4 of target's surface

T1905e

2-D *DRACO* demonstrates good agreement in predicting target performance for shot 35713 (α ~ 4)

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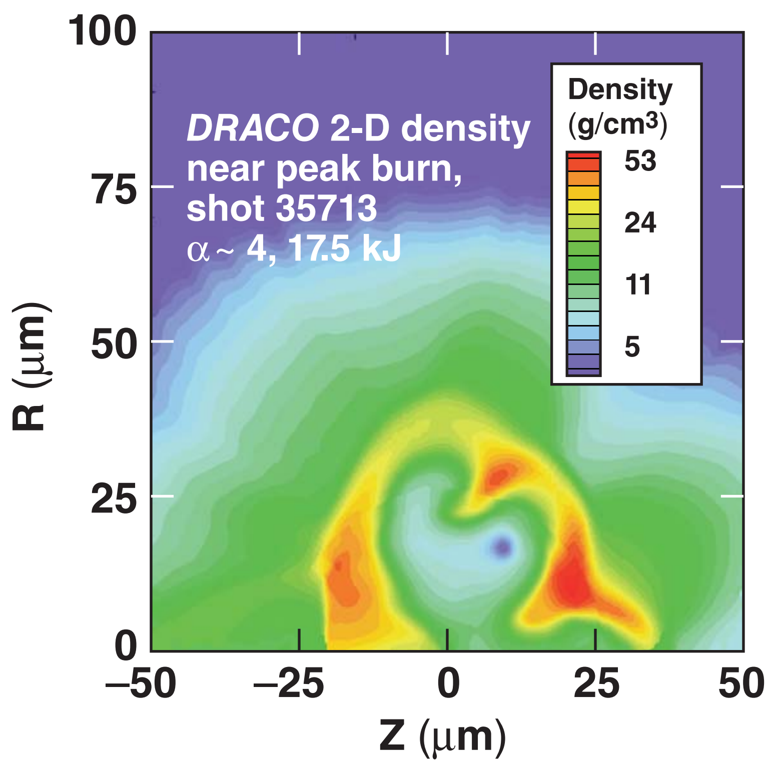
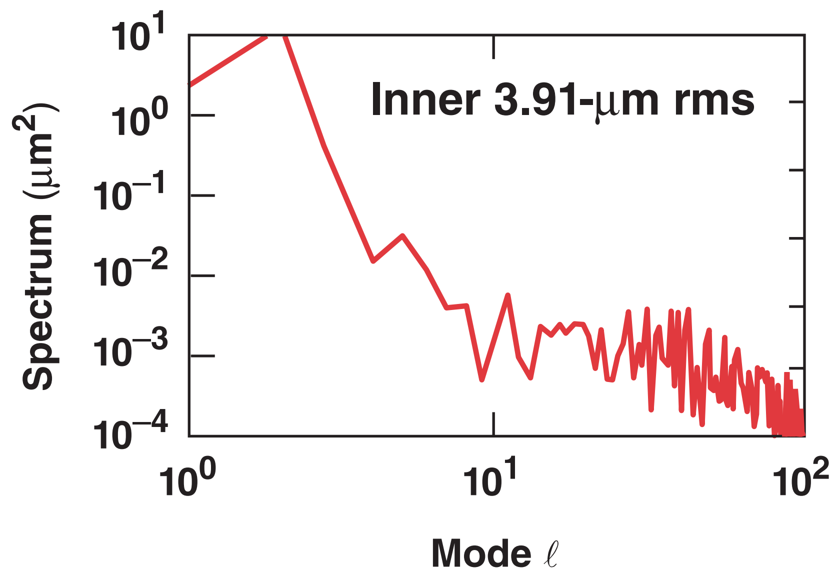




	Expt	1-D	2-D
Y_{1n}	1.61×10^{10}	9.90×10^{10}	1.81×10^{10}
Y_{2n}	2.55×10^{8}	1.70×10^{9}	2.78×10^{8}
$\langle\rho R\rangle$ (mg/cm^2)	88	117	133
T_{ion} (keV)	3.0	1.9	1.70

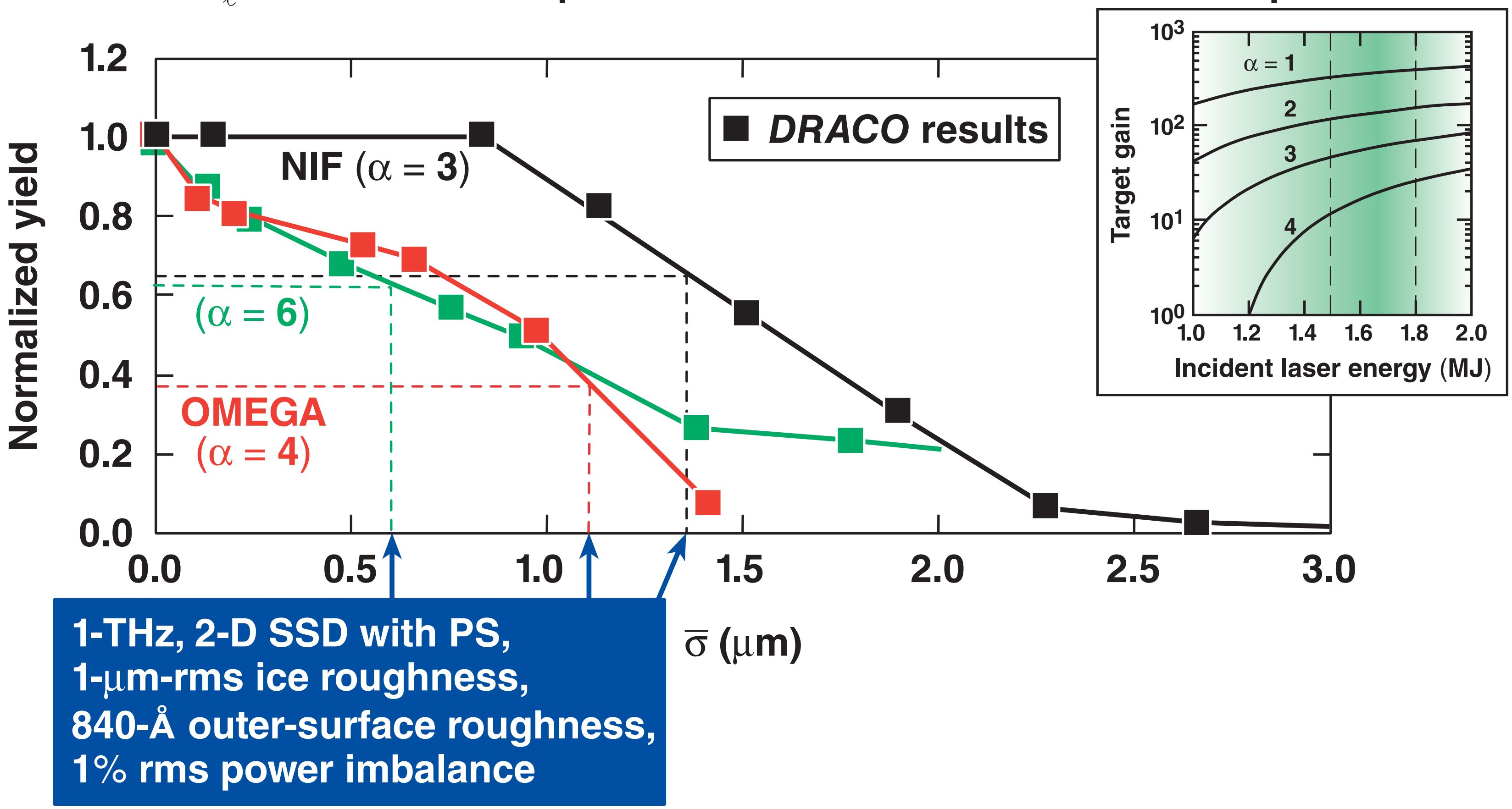
TC6465d

A stability analysis* of the $\alpha = 4$ design defines the ignition-scaling performance window for cryogenic implosions

- The NIF gain and OMEGA yield can be related by

$$\bar{\sigma}^2 = 0.06\,\sigma^2_{\ell<10} + \sigma^2_{\ell\geq 10},$$

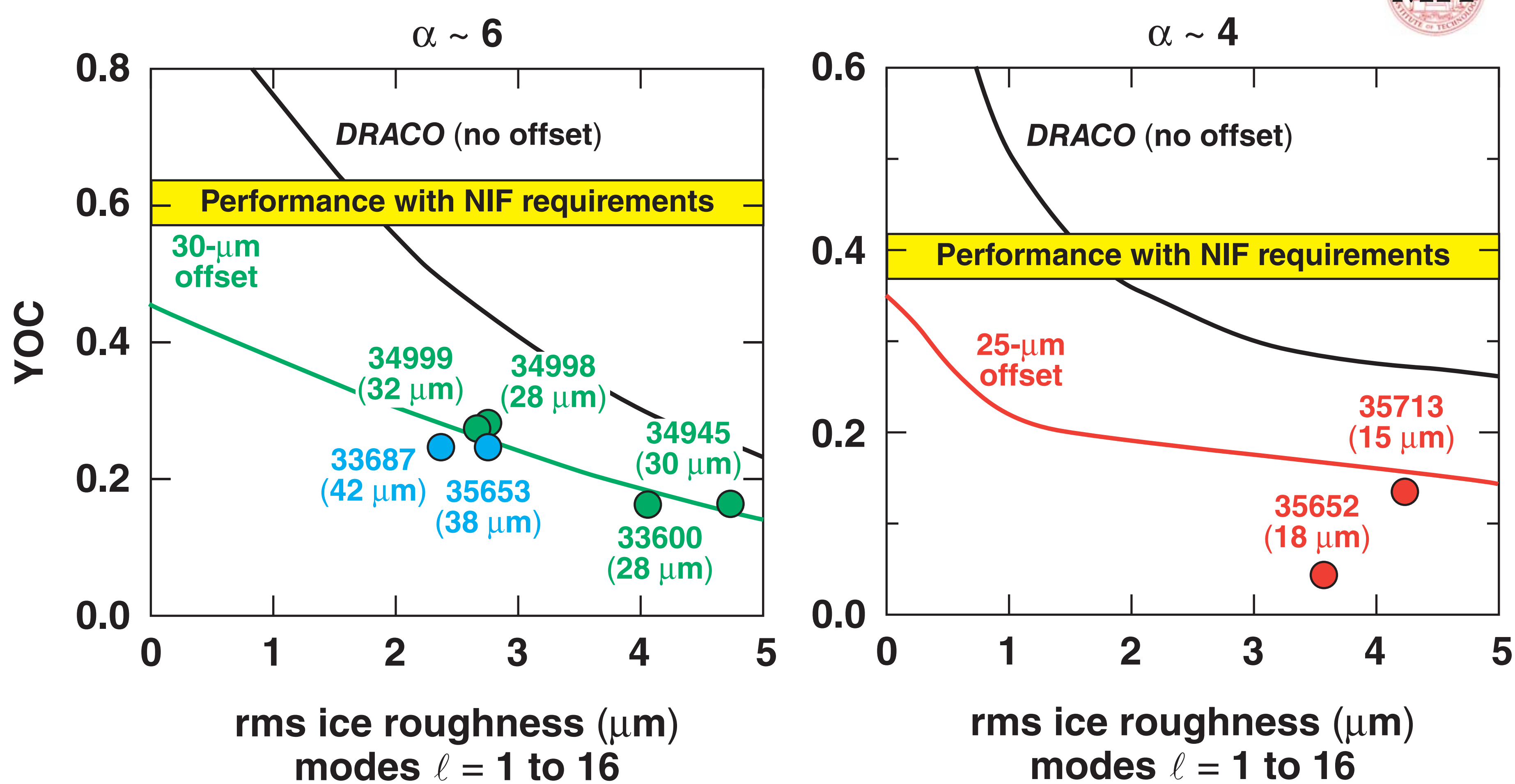
where the σ_ℓ's are the rms amplitudes at the end of the acceleration phase*.



E12008k

*P. McKenty *et al.*, Phys. Plasma 11, 2790 (2004).

Hydrodynamic simulations are consistent with implosion data over a wide range of ice roughness and target offset

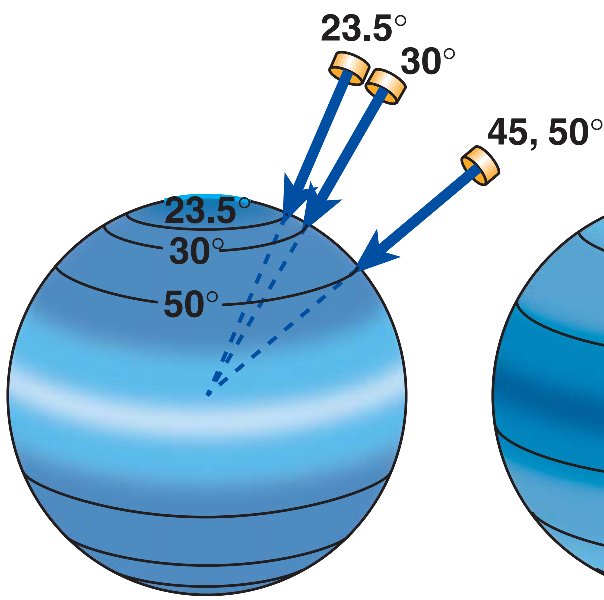


E13085d

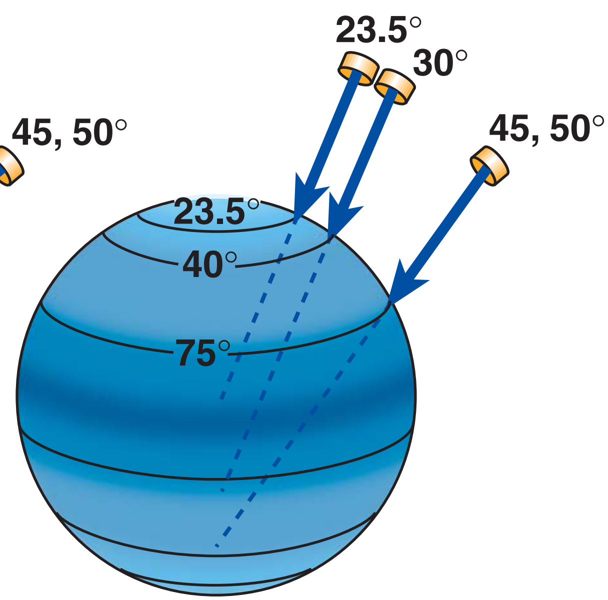
Polar Direct Drive

Direct drive can achieve ignition while the NIF is in the x-ray-drive configuration

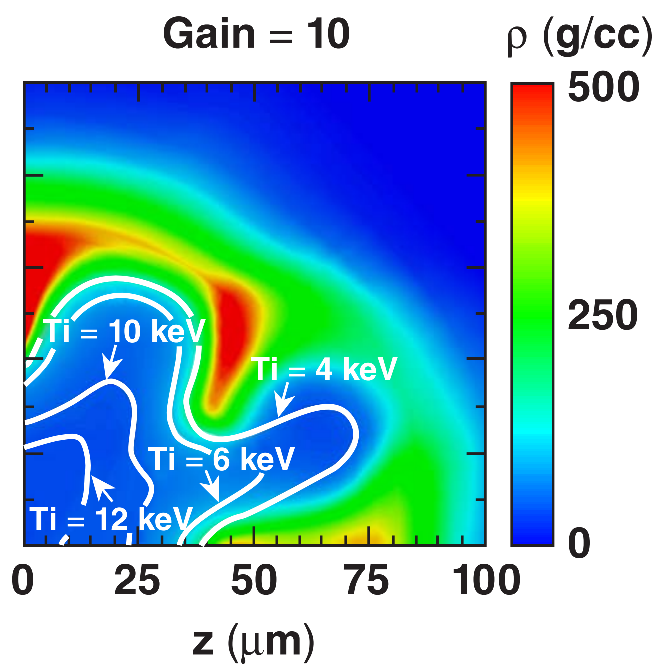
Standard pointing with x-ray-drive configuration



Repointing for PDD



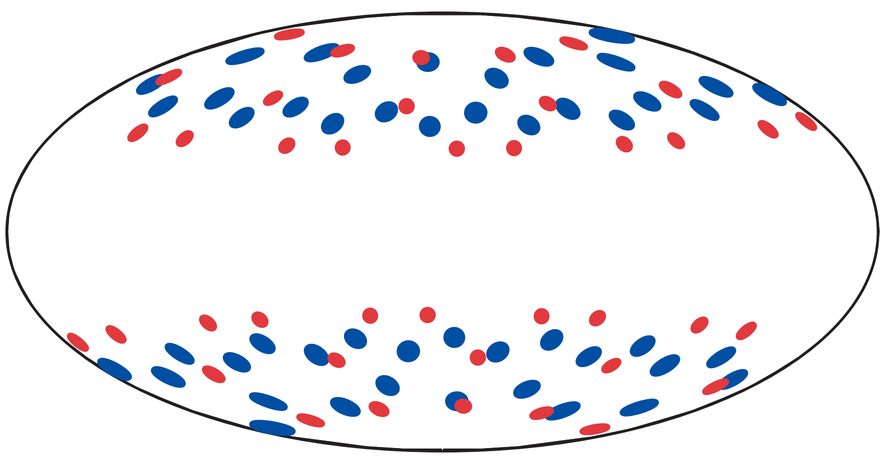
2-D hydrodynamic simulations

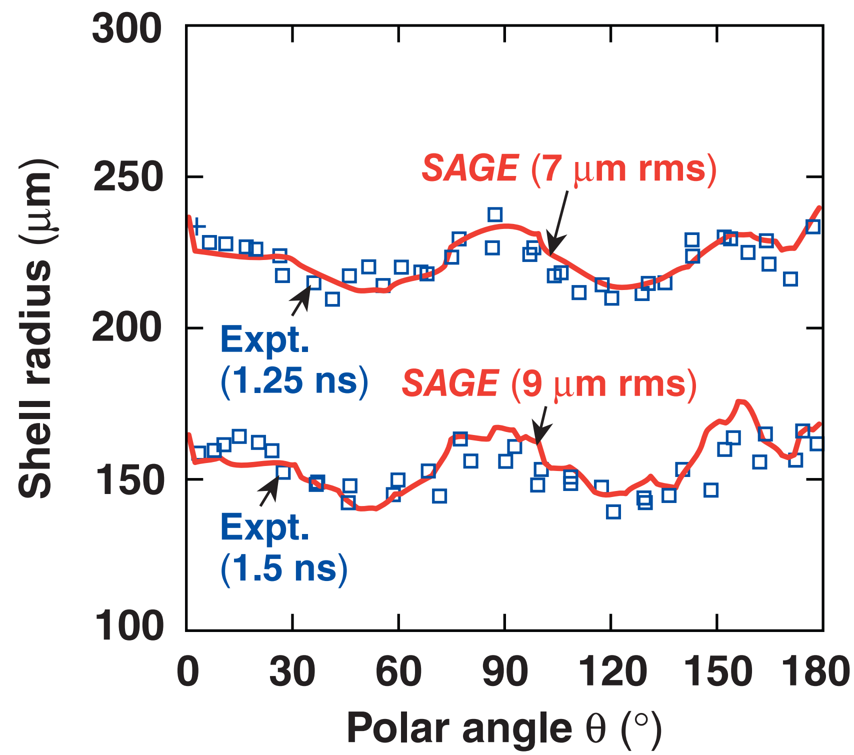


- Polar direct drive (PDD) is based on the optimization of phase-plate design, beam pointing, and pulse shaping.

TC6631a

2-D hydrocode simulations track the measured target nonuniformity for initial PDD experiments on OMEGA





- The NIF PDD configuration with 48 quads has been approximated by repointing 40 beams for implosions on OMEGA

E13488

Fast Ignition

A complementary approach to hot-spot ignition, namely fast ignition is an active area of research at LLE

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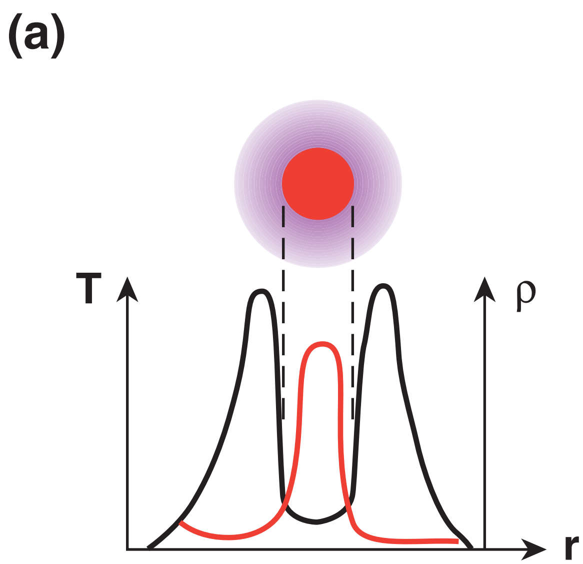
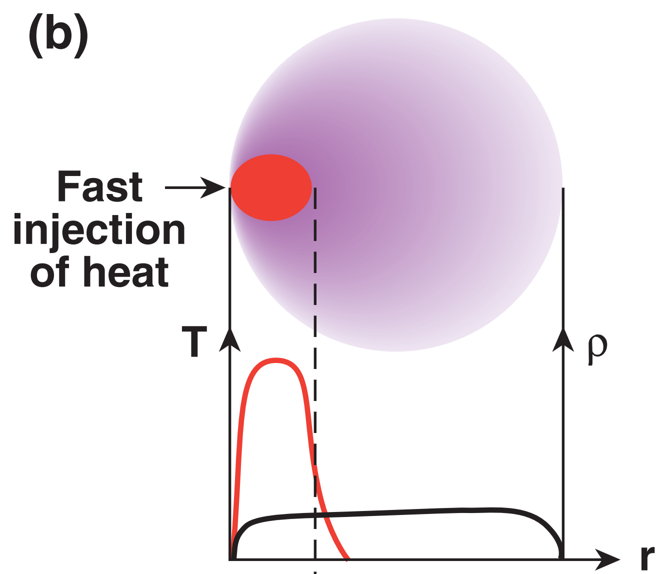
Conventional ICF



Low-density central spot ignites a high-density cold shell
$\rho T_{hot} \approx \rho T_{cold}$ (isobaric)

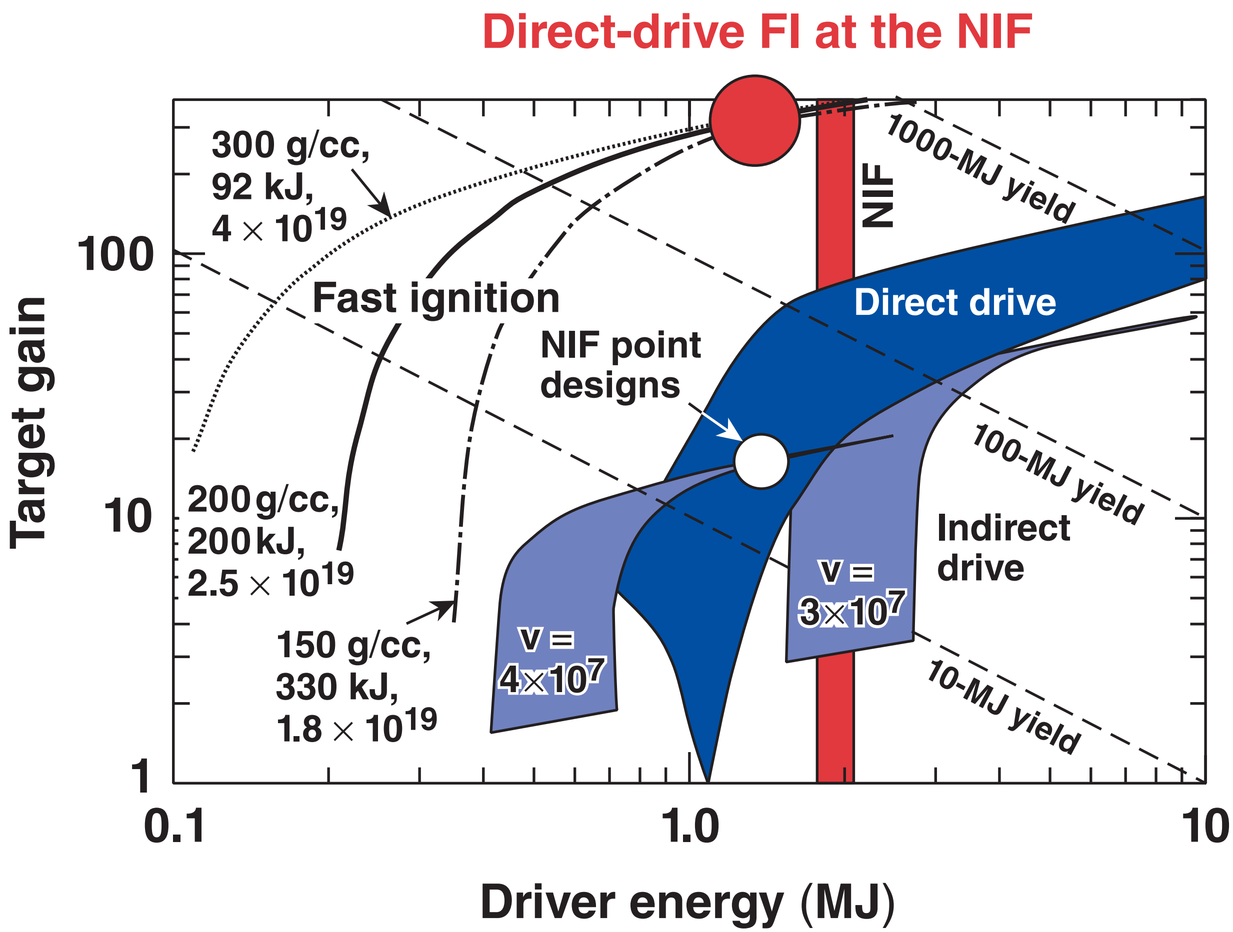
Fast Ignitor



Fast-heated side spot ignites a high-density fuel ball
$\rho_{hot} \approx \rho_{cold}$ (isochoric)

E12526b

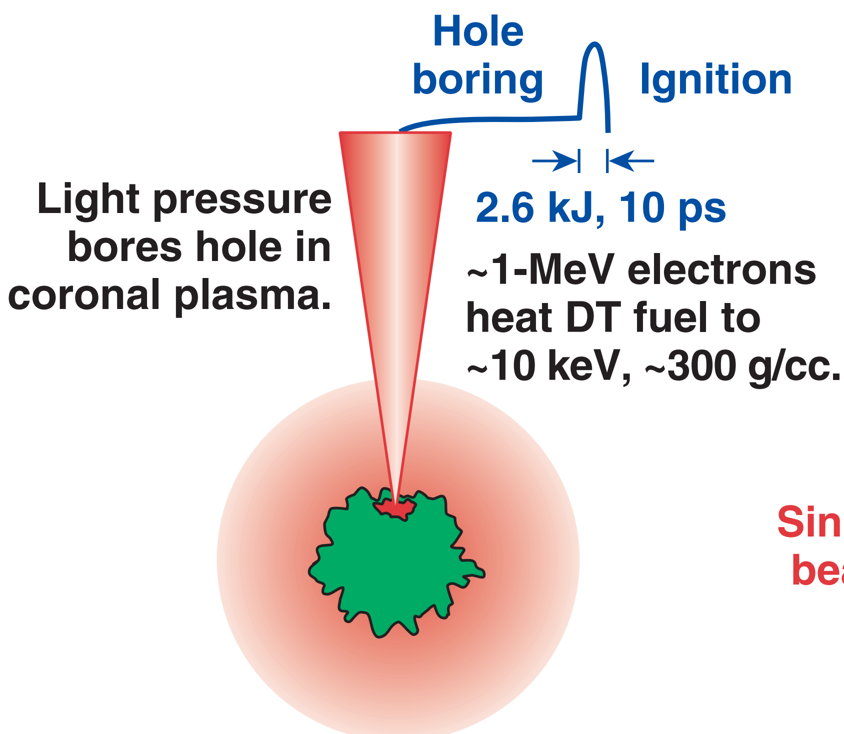
Ignition could be acheived at lower drive energies with fast ignition



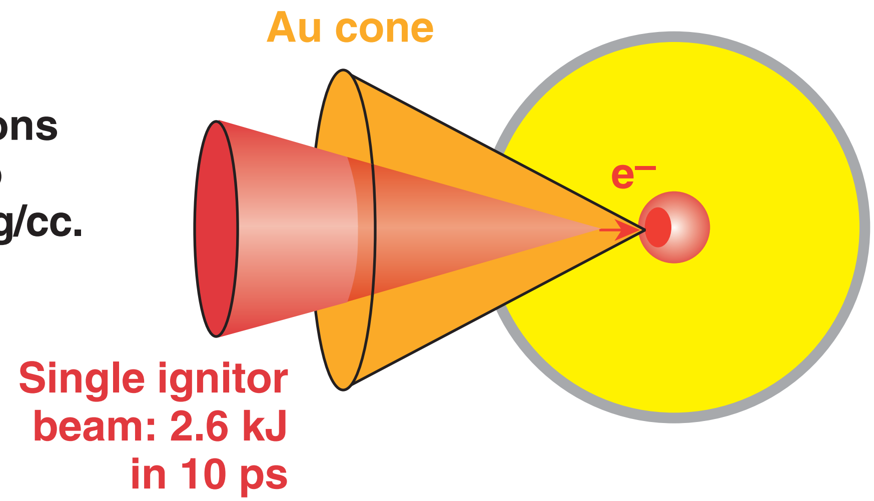
E12527b

The two viable fast-ignition concepts share fundamental issues: hot-electron production and transport to the core

Channeling concept

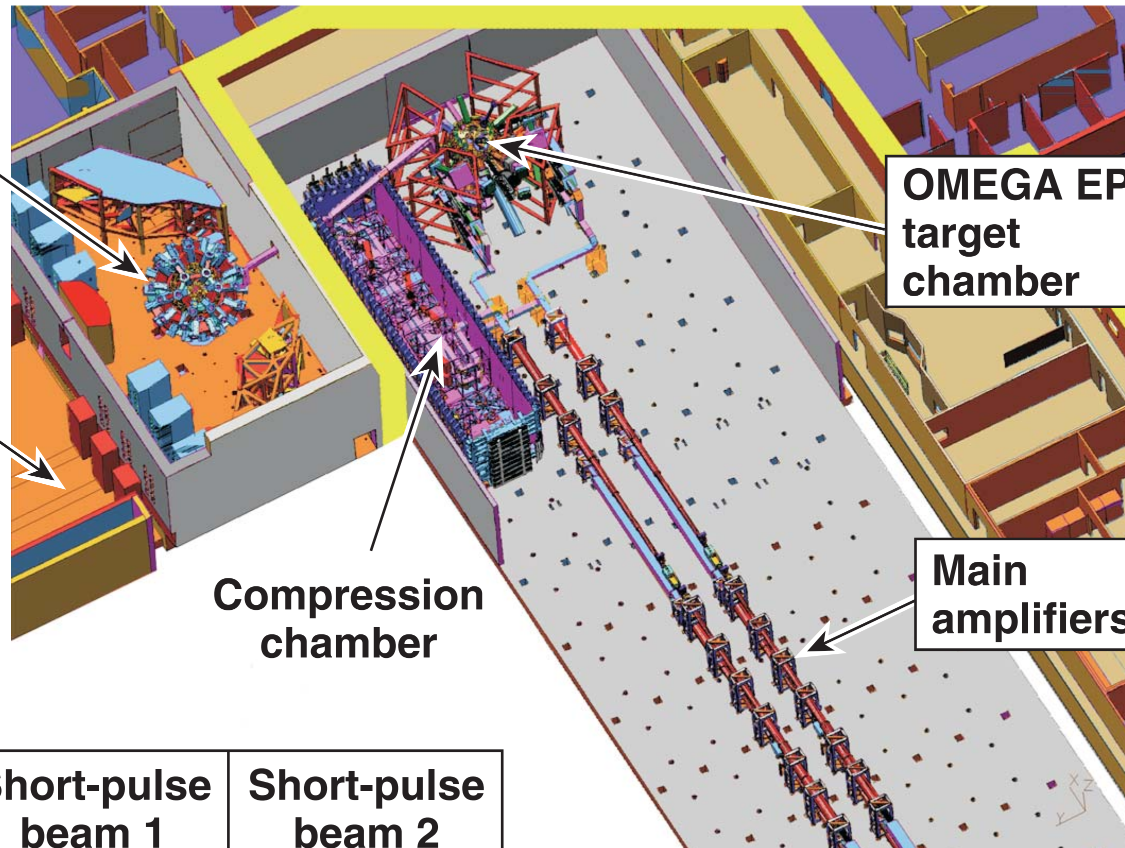


Cone-focused concept



OMEGA EP

Fast ignition with cryogenic fuel will be conducted on OMEGA with the high energy petawatt OMEGA EP



Short-pulse performance	Short-pulse beam 1	Short-pulse beam 2
Short pulse (IR)	1 to 100 ps	35 to 100 ps
IR energy on-target (kJ)	2.6	2.6
Intensity (W/cm^2)	6×10^{20}	~ 4×10^{18}

OMEGA EP will be completed in FY07

G5546p

Summary/Conclusions

Significant theoretical and experimental progress continues to be made at LLE – charting the path to ignition with direct-drive ICF

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- Direct drive targets are predicted to ignite on the NIF while it is in x-ray-drive configuration with polar direct drive (PDD).
- Fully integrated fast-ignition (FI) experiments will begin on OMEGA with the completion of the high energy petawatt (HEPW) upgrade – OMEGA EP.

Prospects for thermonuclear ignition with direct drive on the NIF are extremely promising.

Gas-tight fast-ignition targets were developed for fuel-assembly experiments

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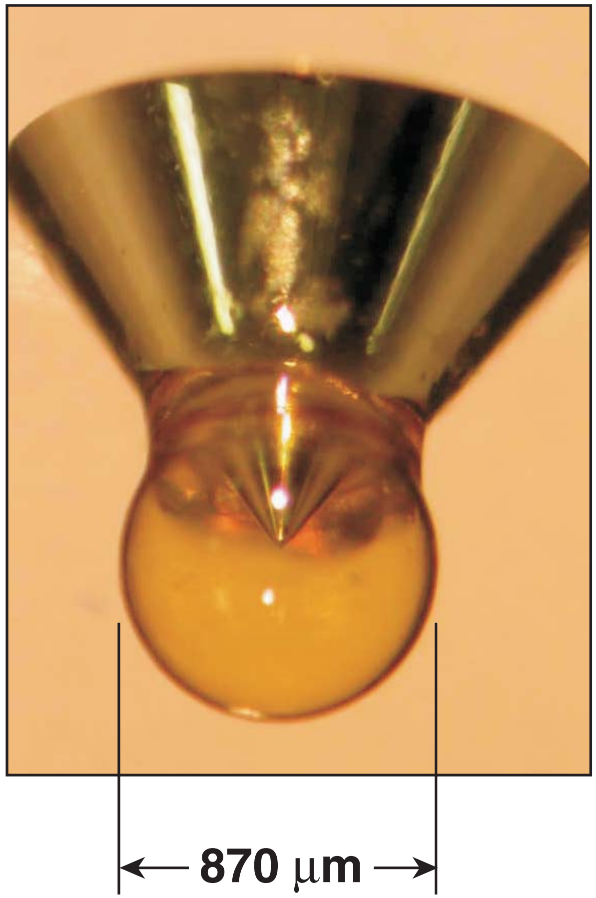
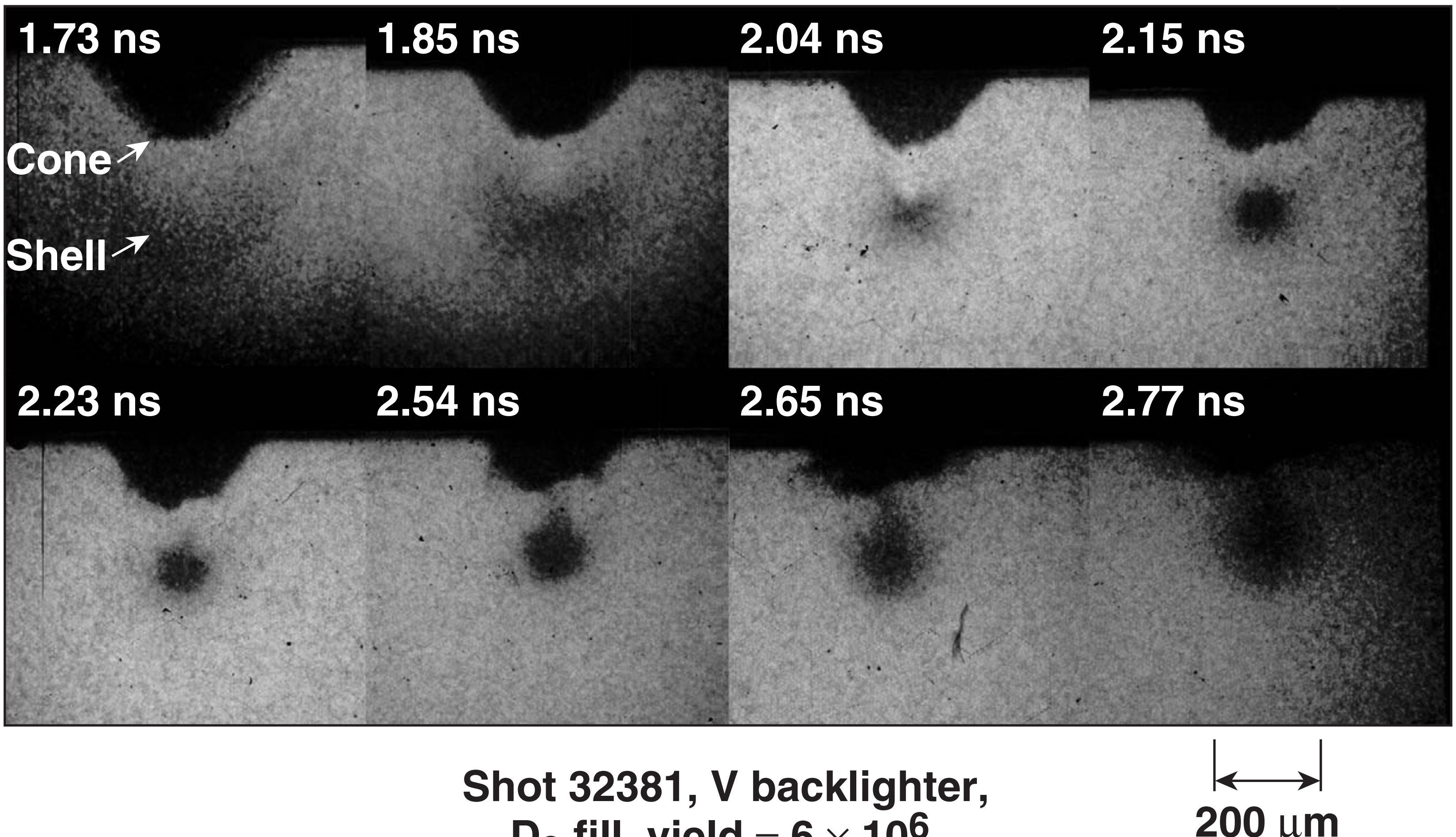
GENERAL ATOMICS

- 870-μm OD shell
- 24-μm wall
- ~10 atm D_2 or D^3He fill
- 35° half-angle gold cone
- Backlighting
  - 35 beams, 12 kJ, 1 ns on target
  - 15 beams, 6 kJ, 1 ns on backlighter
- Areal-density measurements
  - 55 beams, 22 kJ, 1 ns on target



The backlit framing-camera images show the core assembly and cone reaction in great detail



Shot 32381, V backlighter,
D_2 fill, yield $= 6 \times 10^6$,
$\rho R \sim 60\ mg/cm^2$ (D^3He proton dE/dx)

E12558d