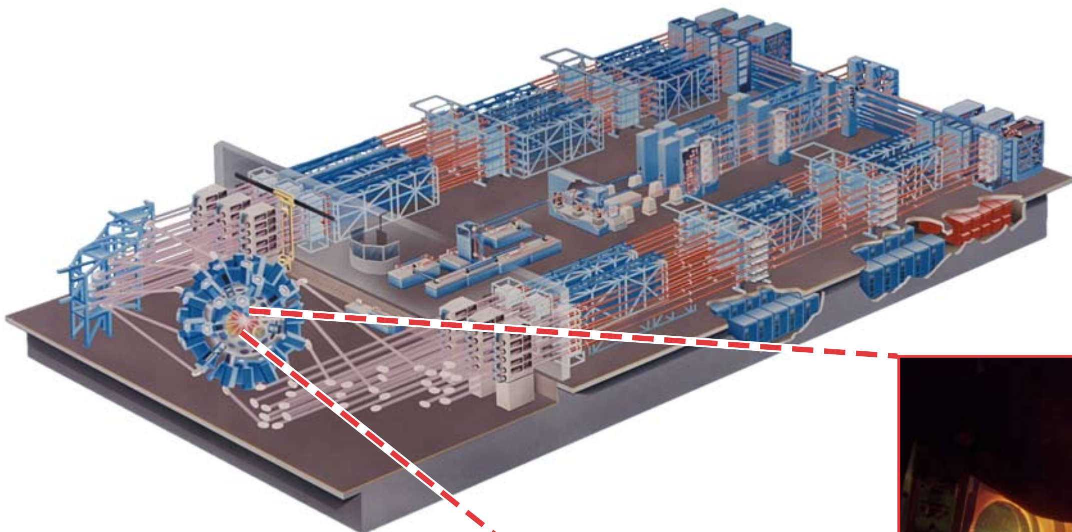
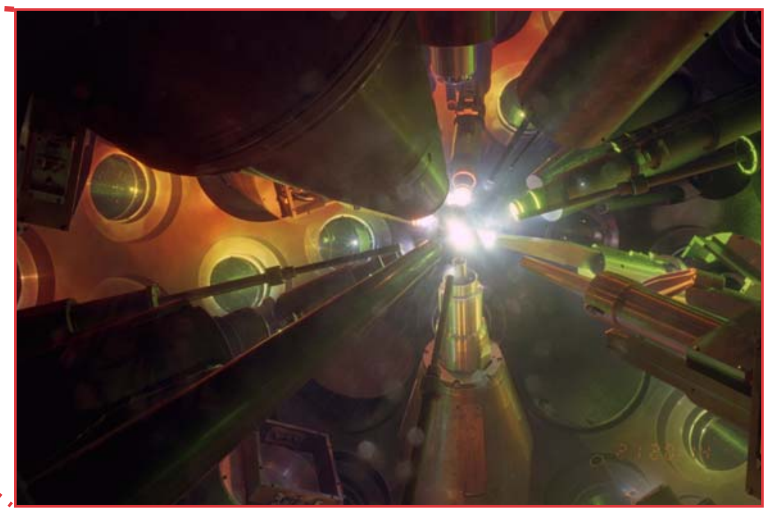
Direct-Drive Inertial Confinement Fusion: Status and Future





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Summary

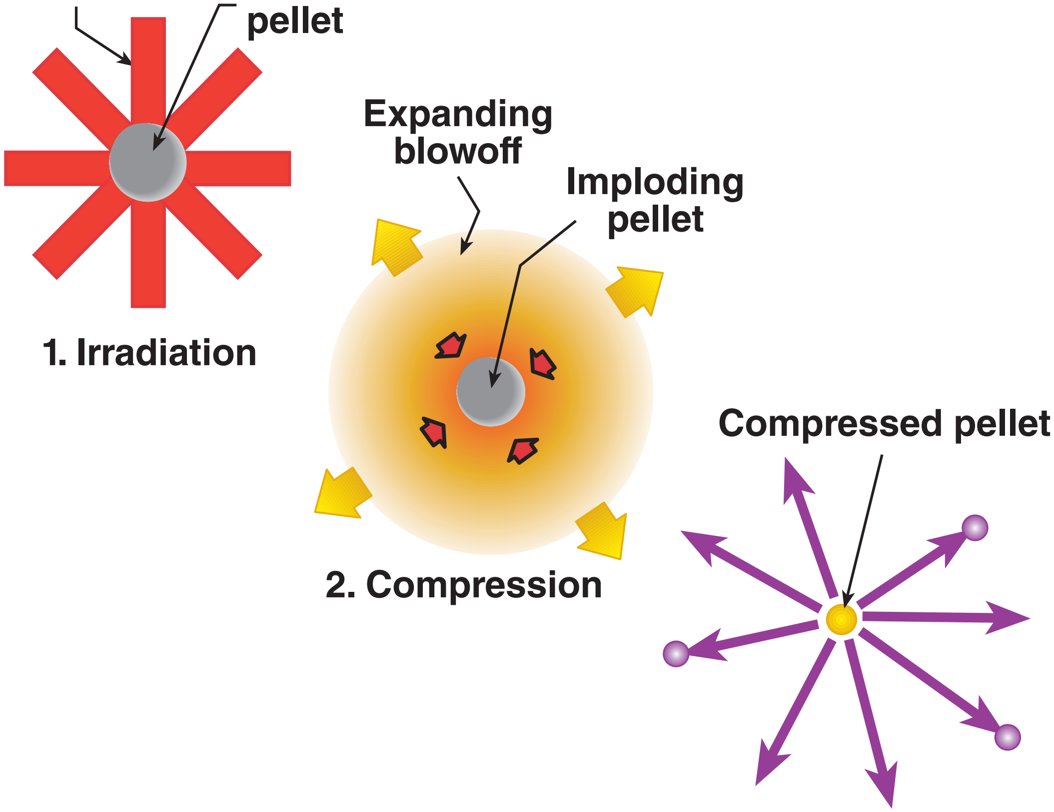
Direct-drive holds great promise for ignition on the National Ignition Facility (NIF)

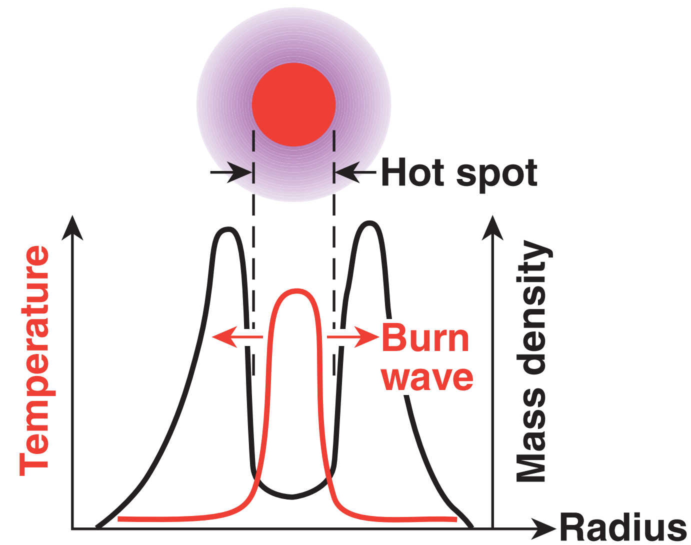
- Two paths to direct-drive ignition on the NIF have been identified—symmetric and polar.
- Good agreement between predictive simulations and ignition-scaled cryogenic implosions is obtained on the OMEGA laser for symmetric drive.
- Polar direct drive may allow for ignition on the NIF in its x-ray drive configuration.
- A new high-energy petawatt capability at OMEGA (OMEGA-EP) will provide the ability to image core distortions in cryogenic implosions and test fast-ignition concepts.

Outline

- Brief introduction to direct-drive
- Symmetric drive
- Polar direct drive
- Fast ignition

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



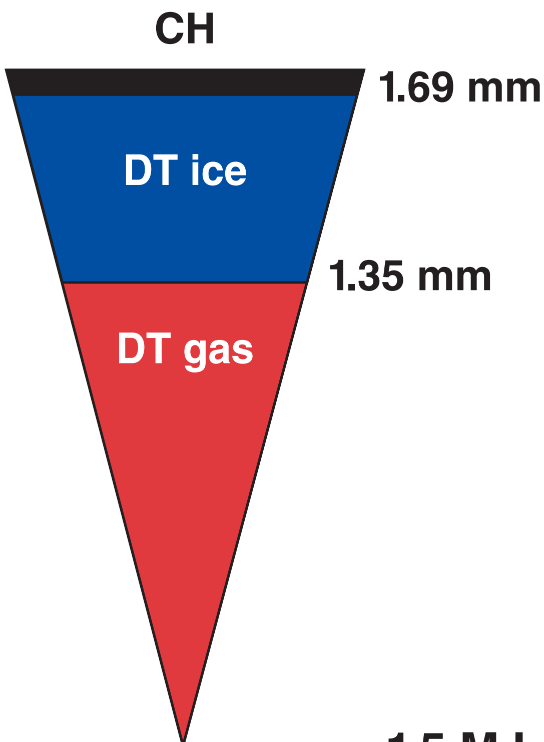


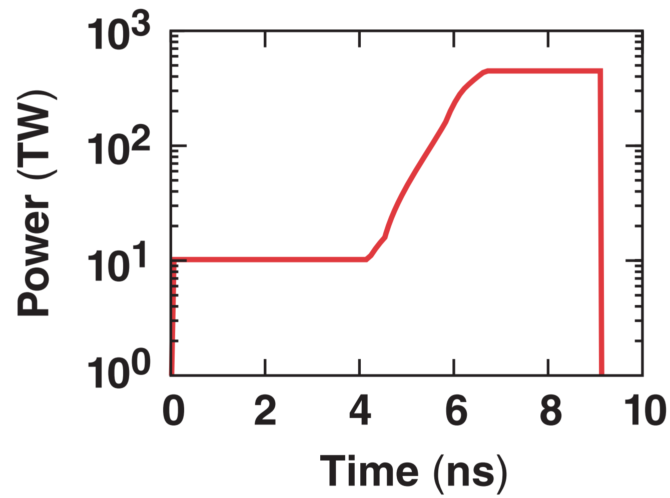
"Hot-spot" ignition requires the core temperature to be at least 10 keV and the core fuel areal density to exceed ~300 mg/cm^2.

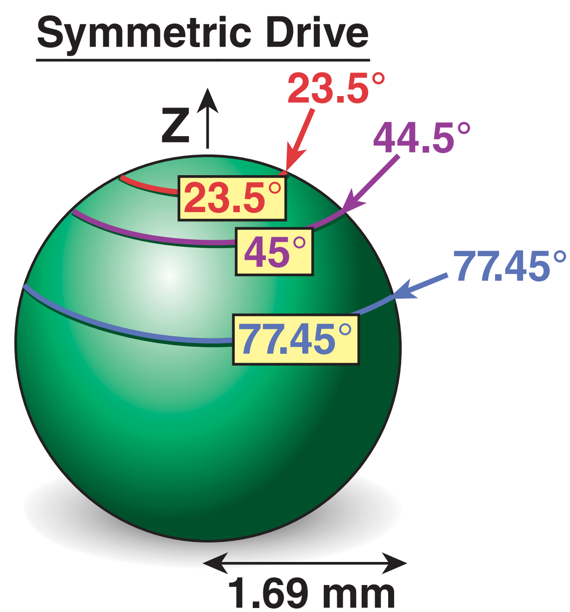
S5g

Symmetric Drive

The NIF direct-drive point design is a thick DT-ice layer enclosed by a thin CH shell







	1.5 MJ
Absorption fraction:	63%
Gain (fusion energy out / laser energy in):	45

TC5576b

A number of key physics issues associated with capsule implosions are being investigated at LLE

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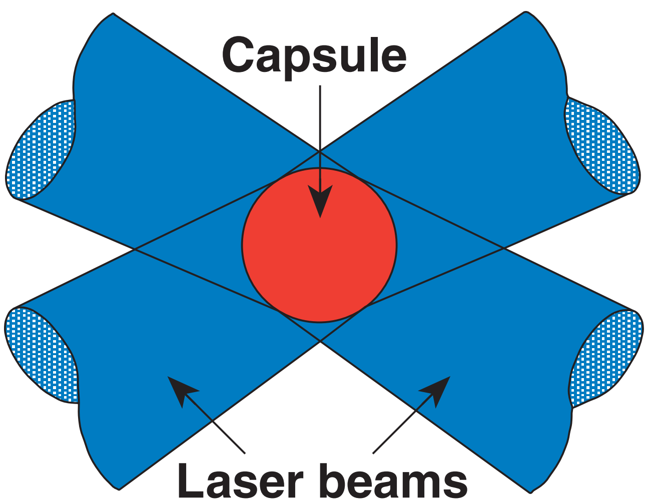
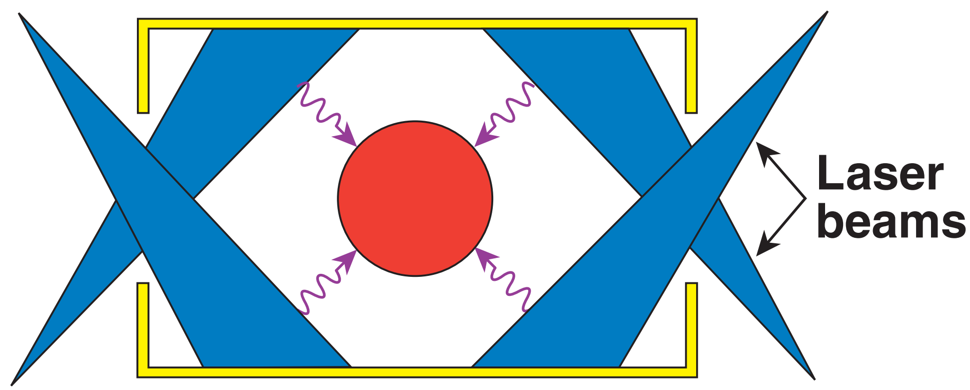
Direct-drive target



X-ray-drive target



Hohlraum using
a cylindrical high-Z case

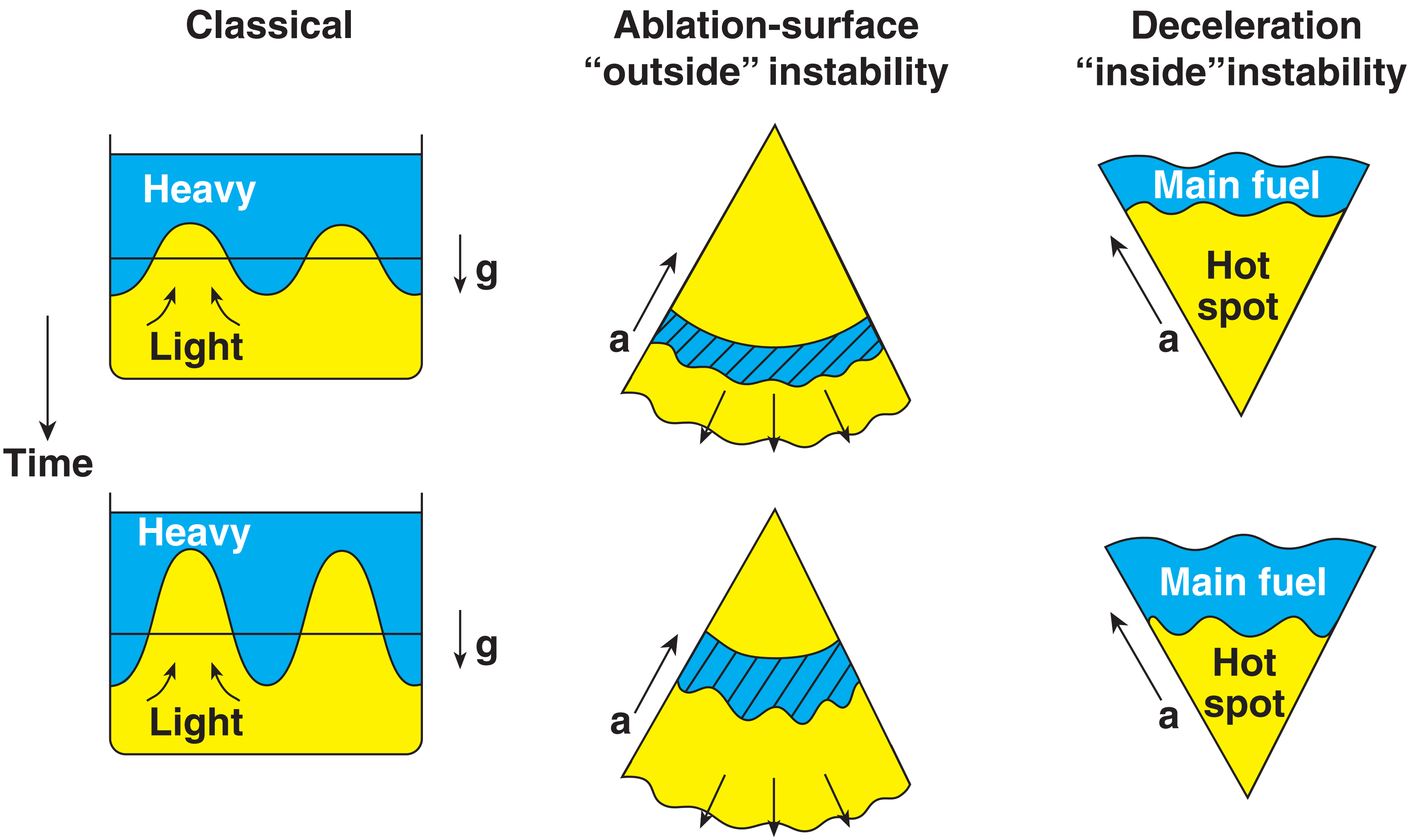
Key issues:

- Energy coupling
- Drive uniformity
- Hydrodynamic instabilities

E6426i

Hydrodynamic Instabilities

The Rayleigh–Taylor instability can reduce target performance



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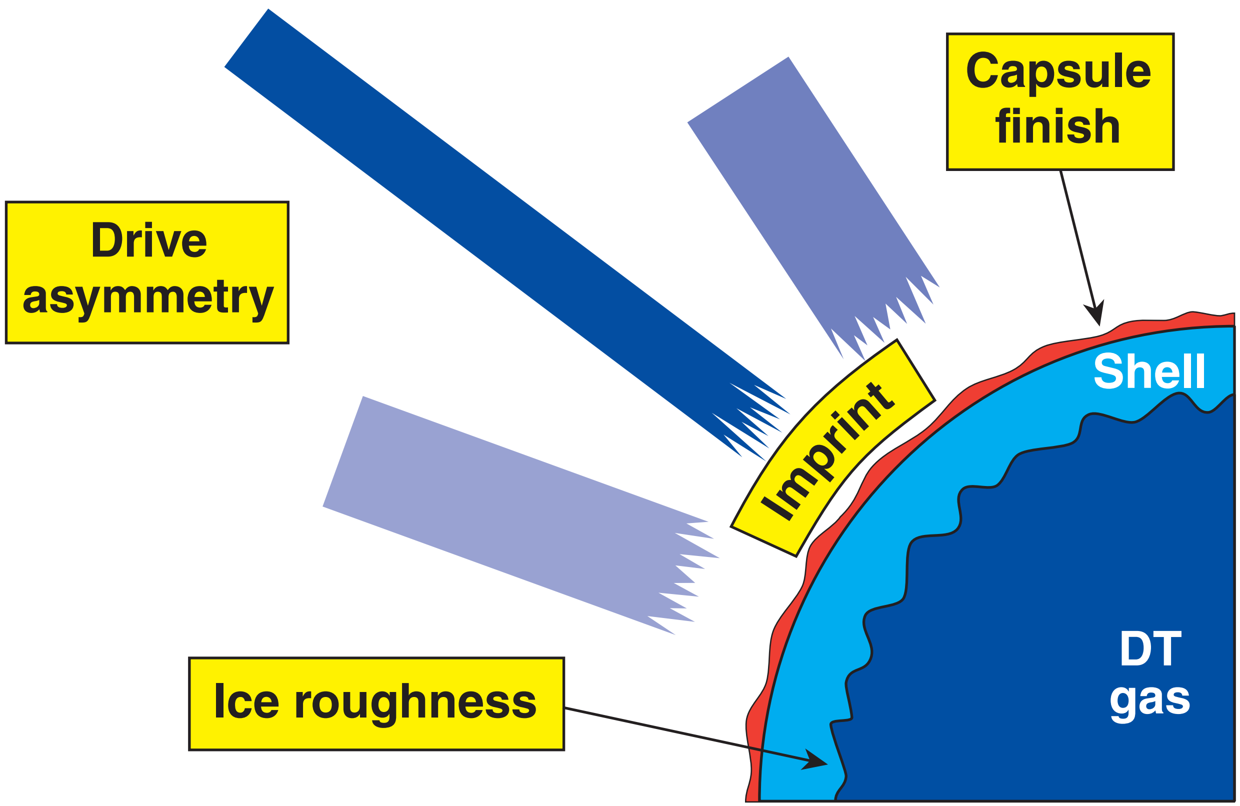
There are four sources of perturbations a direct-drive capsule must tolerate to ignite and burn



Control of target and irradiation nonuniformity and subsequent instability growth provides the greatest challenge to direct-drive ignition.

TC6610a

Example of laser nonuniformity: application of single-beam smoothing* is necessary for ignition

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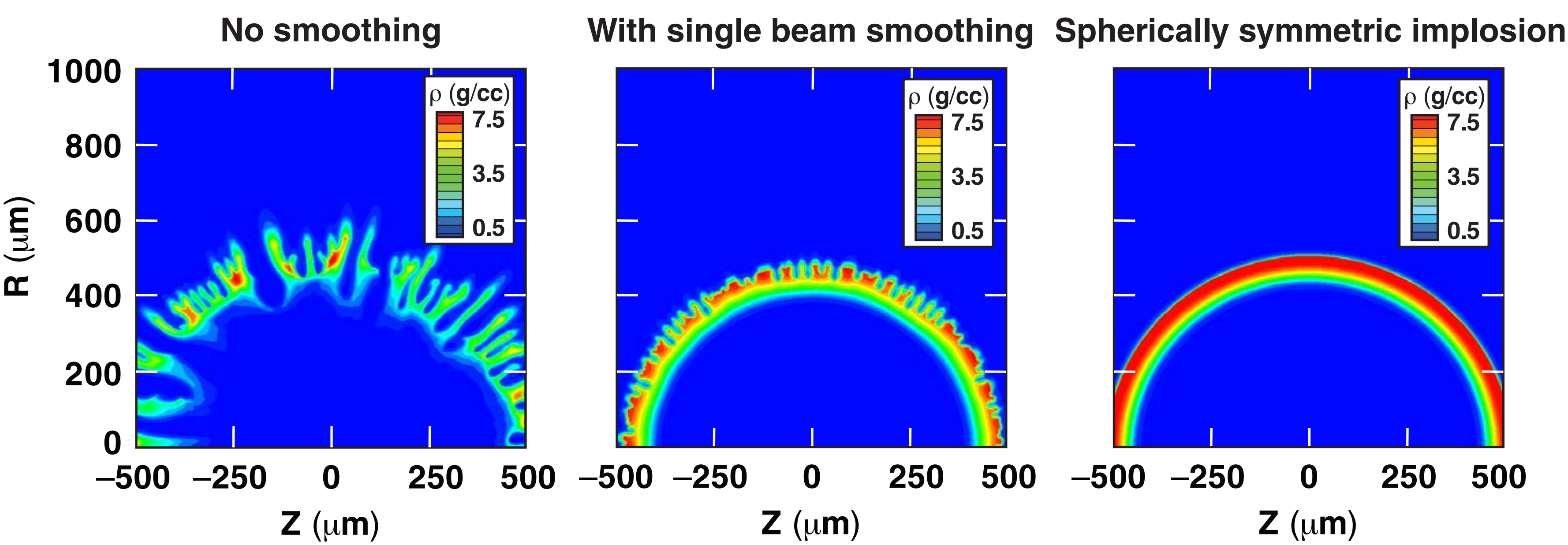
2-D simulation of Direct Drive Capsule at the end of Acceleration



The NIF direct-drive point design ignites with a gain of 30 when nonuniformities are included in the simulations.**

*S. Skupsky *et al*., J. Appl. Phys. 66, 3456 (1989).
**P. McKenty *et al*., Phys. Plasmas 8, 2315 (2001).

TC5587g

The OMEGA laser is designed to achieve high uniformity with flexible pulse-shaping capability

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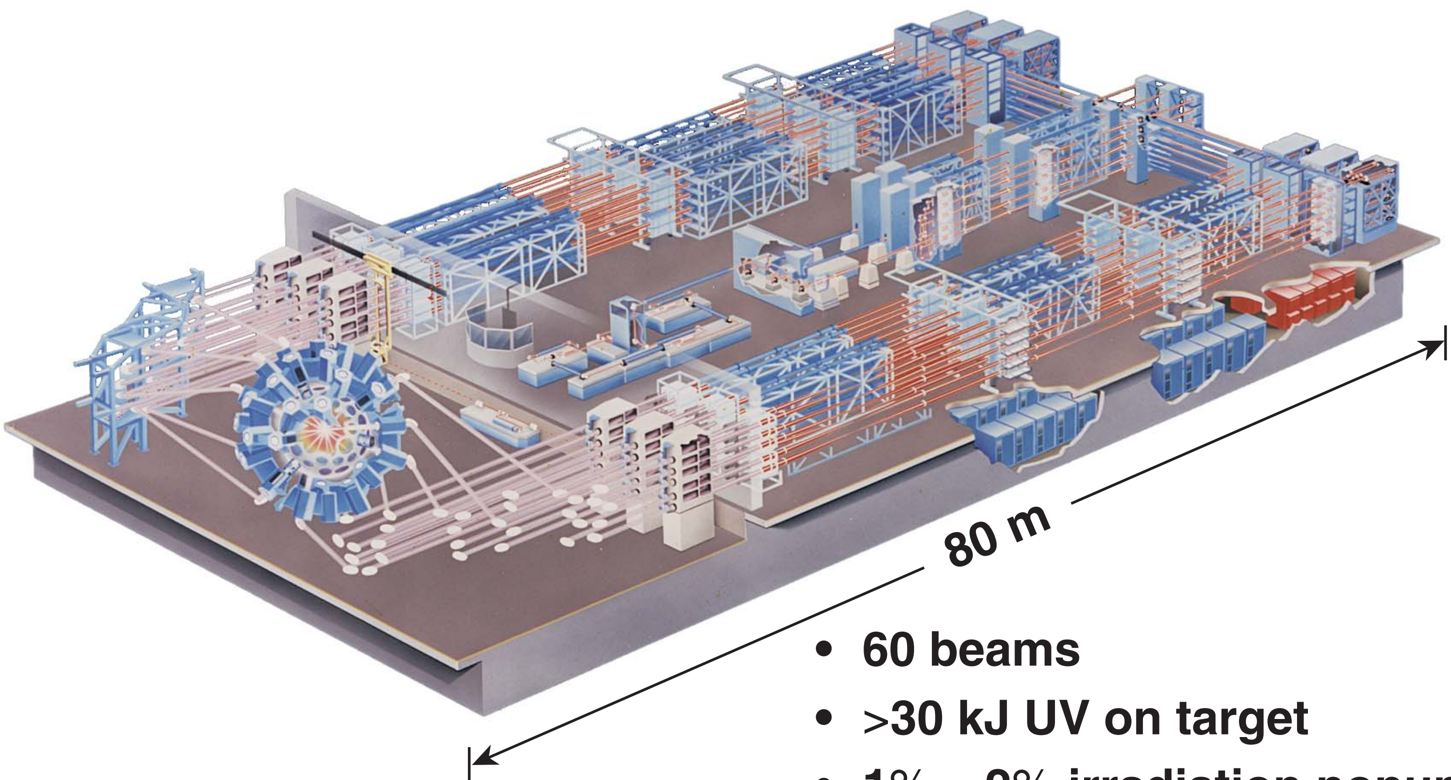
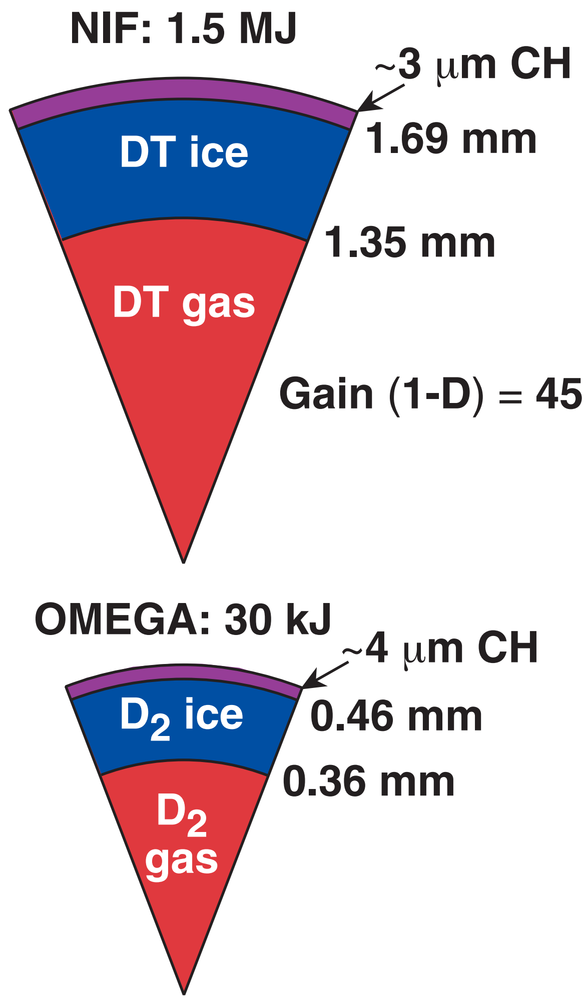


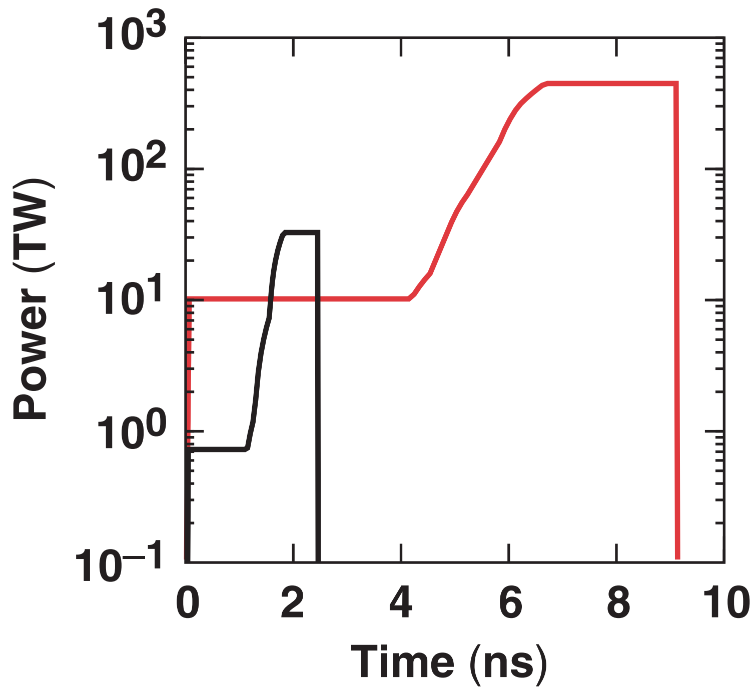
- 60 beams
- >30 kJ UV on target
- 1% – 2% irradiation nonuniformity with 1 THz 2-D SSD, polarization smoothing phase plates, power balance
- Flexible pulse shaping
- Short shot cycle (1 h)
- A wide range of implosion diagnostics

TC2998v

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



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



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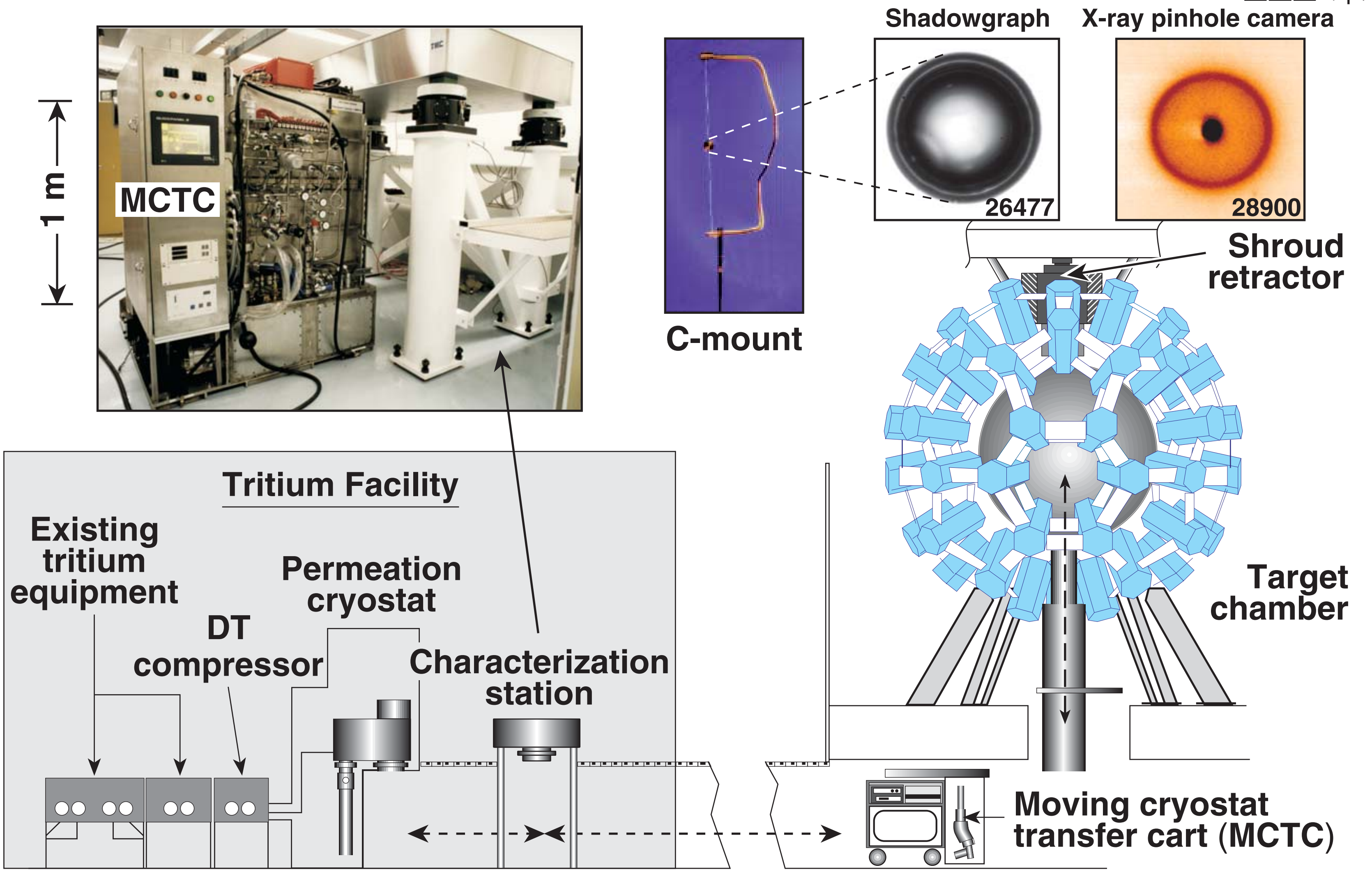
The life cycle of a cryogenic target is an engineering tour de force



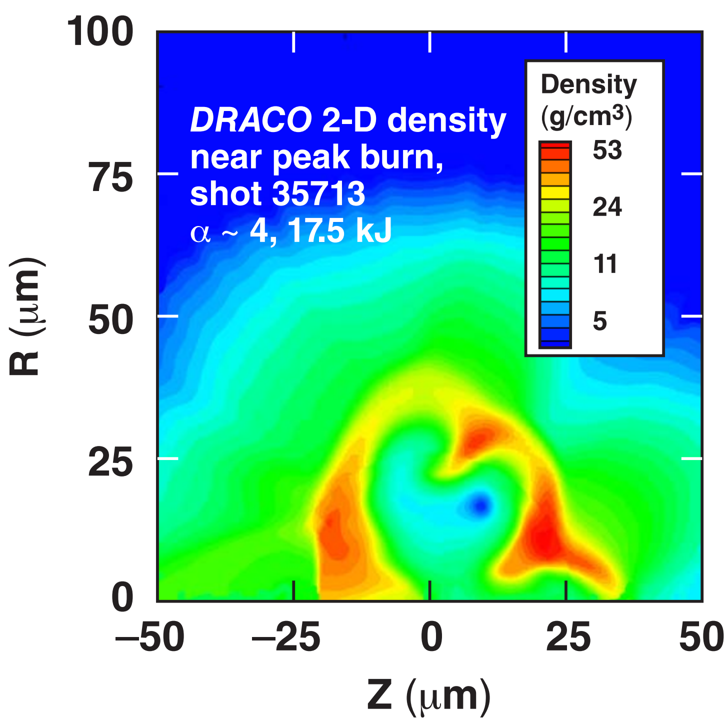
- **Target positioning accuracy is more challenging with cryogenic targets.**

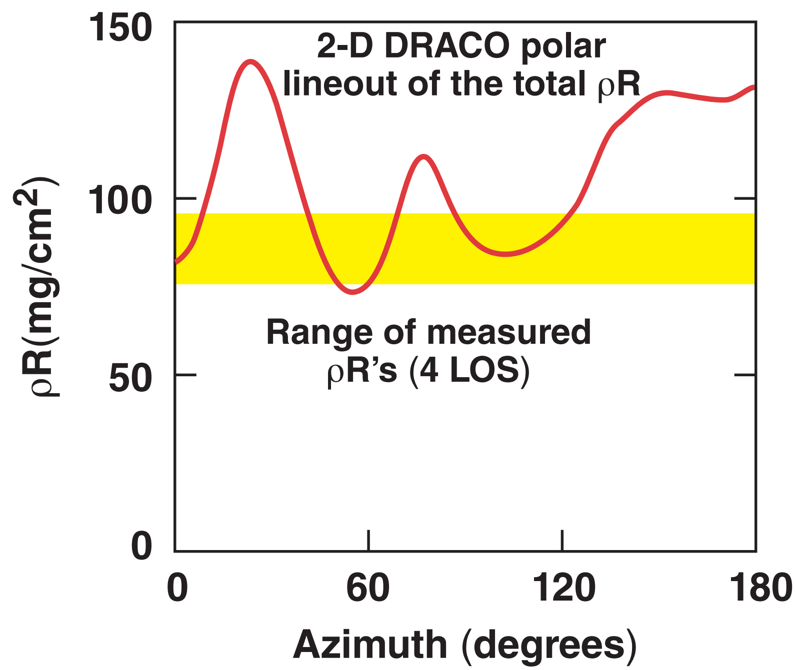
E12062c

A 2-D hydrodynamic simulation demonstrates good agreement in predicting target performance for shot 35713 ($\alpha \sim 4$)

	1-D	2-D	Expt
Y_{1n}	9.1×10^{10}	1.8×10^{10}	1.6×10^{10}
Y_{2n}	1.7×10^{9}	2.8×10^{8}	2.6×10^{8}
$\langle \rho R \rangle$ (mg/cm^2)	117	101	88
T_{ion} (keV)	1.9	1.7	3.0

15µm offset, 4.1 µm ice rms





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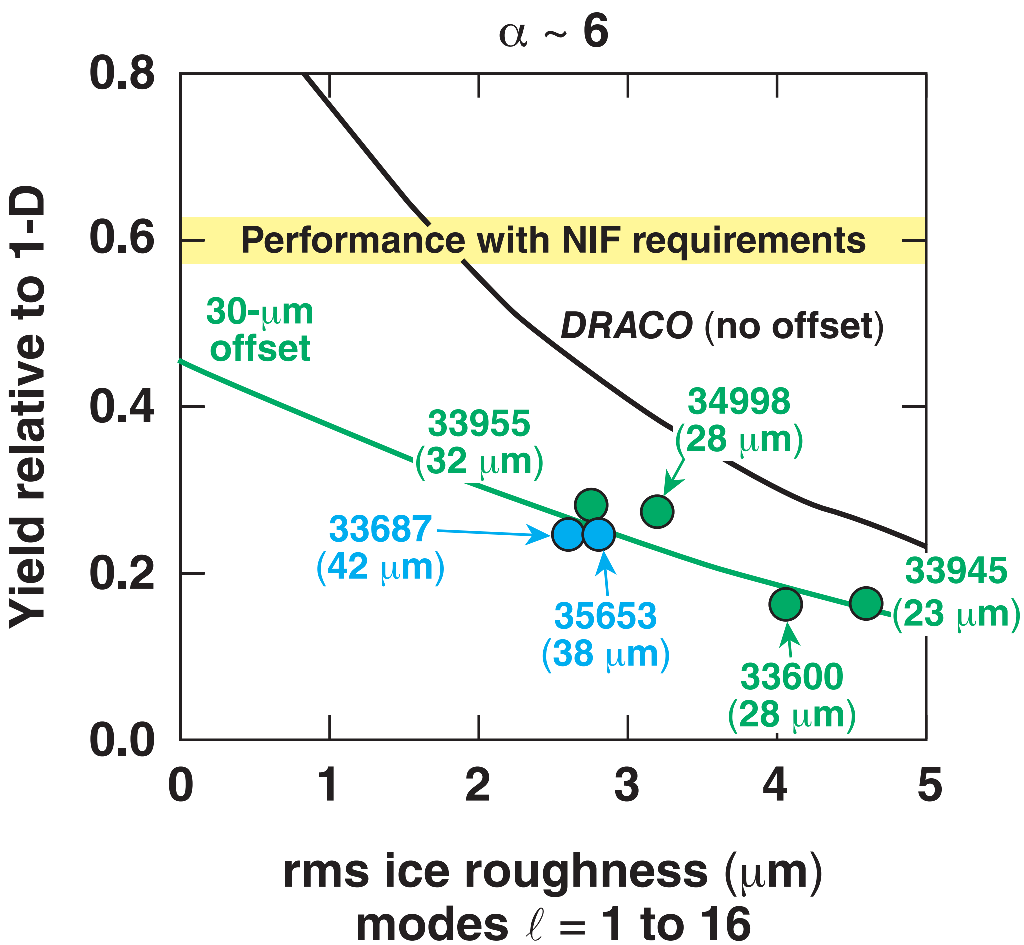
Hydrodynamic simulations are consistent with implosion data over a wide range of ice roughness and target offset



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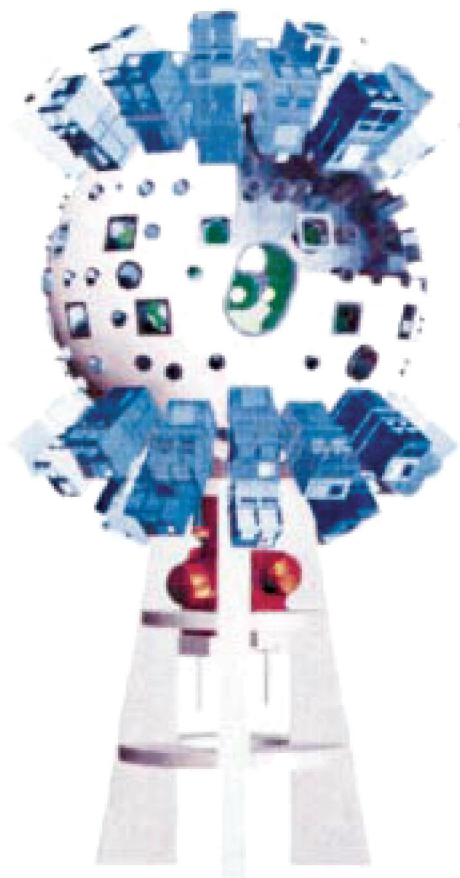
Conversion to direct drive requires the addition of optics to the midplane of the NIF target chamber

Indirect Drive



Direct Drive

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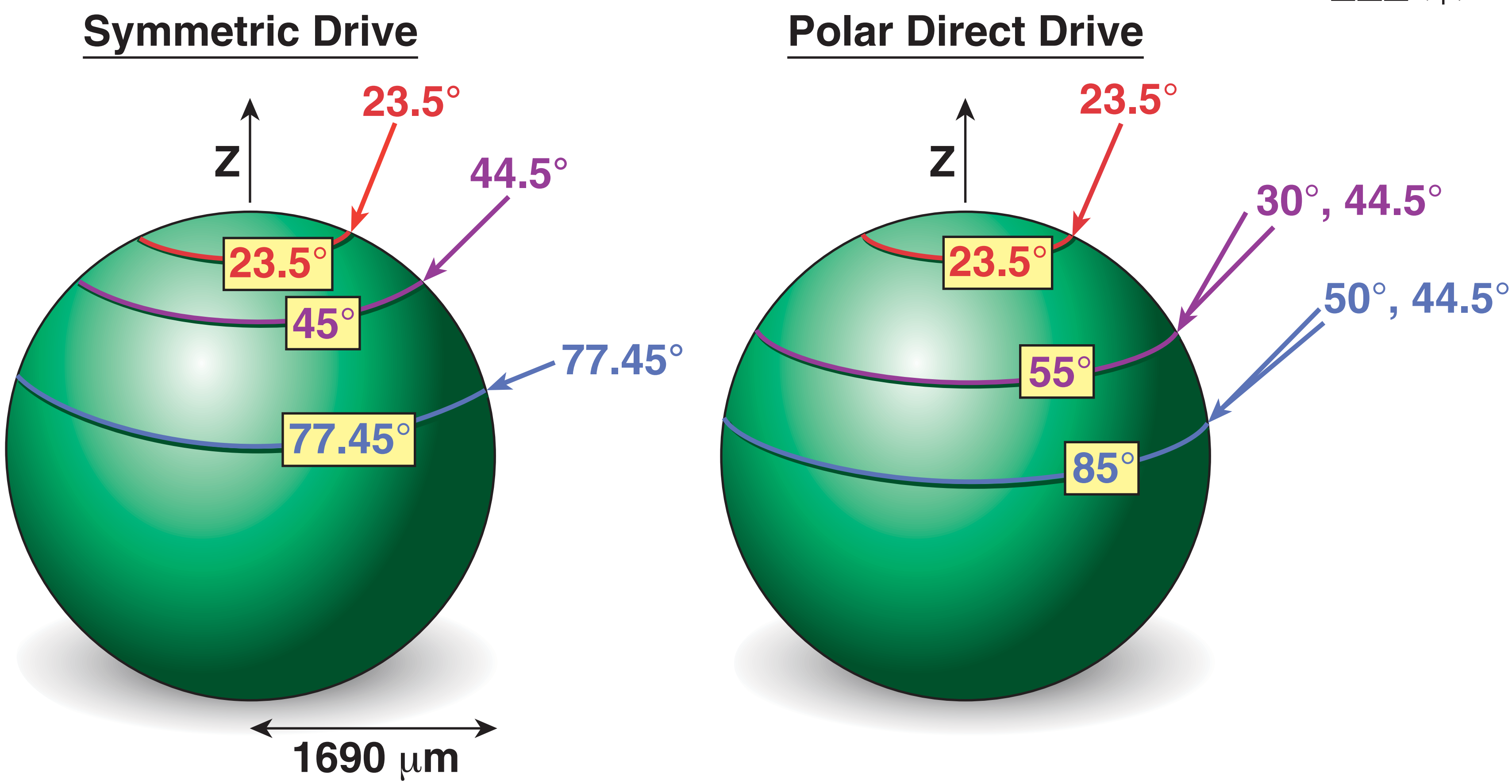
Polar Direct Drive

Polar direct drive (PDD) enables ignition experiments while the NIF is in its x-ray drive configuration

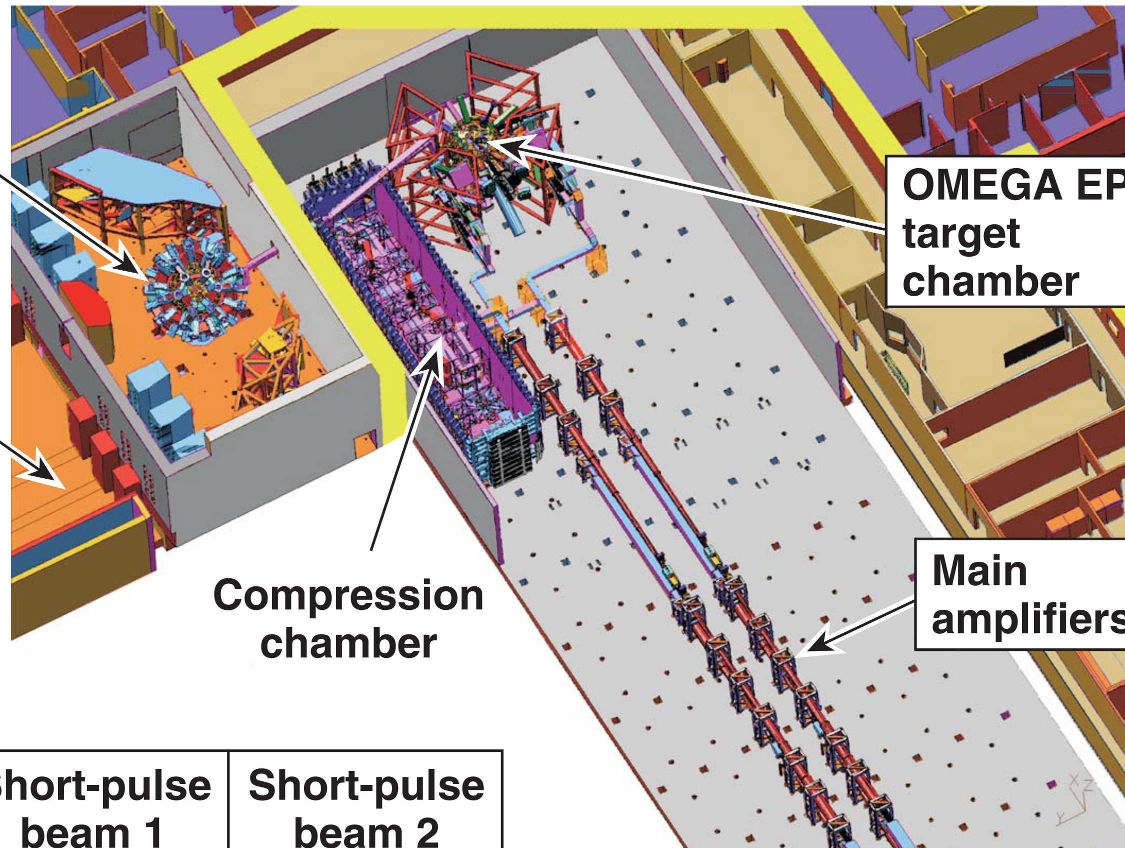


- Refractive losses due to higher angles of incidence at the equator can be compensated for by varying pulse shapes.
- Preliminary 2-D simulations of PDD achieve ignition with gain 30.

TC6892

OMEGA EP: ICF Program

OMEGA EP will be used to backlight cryogenic implosions and study fast ignition

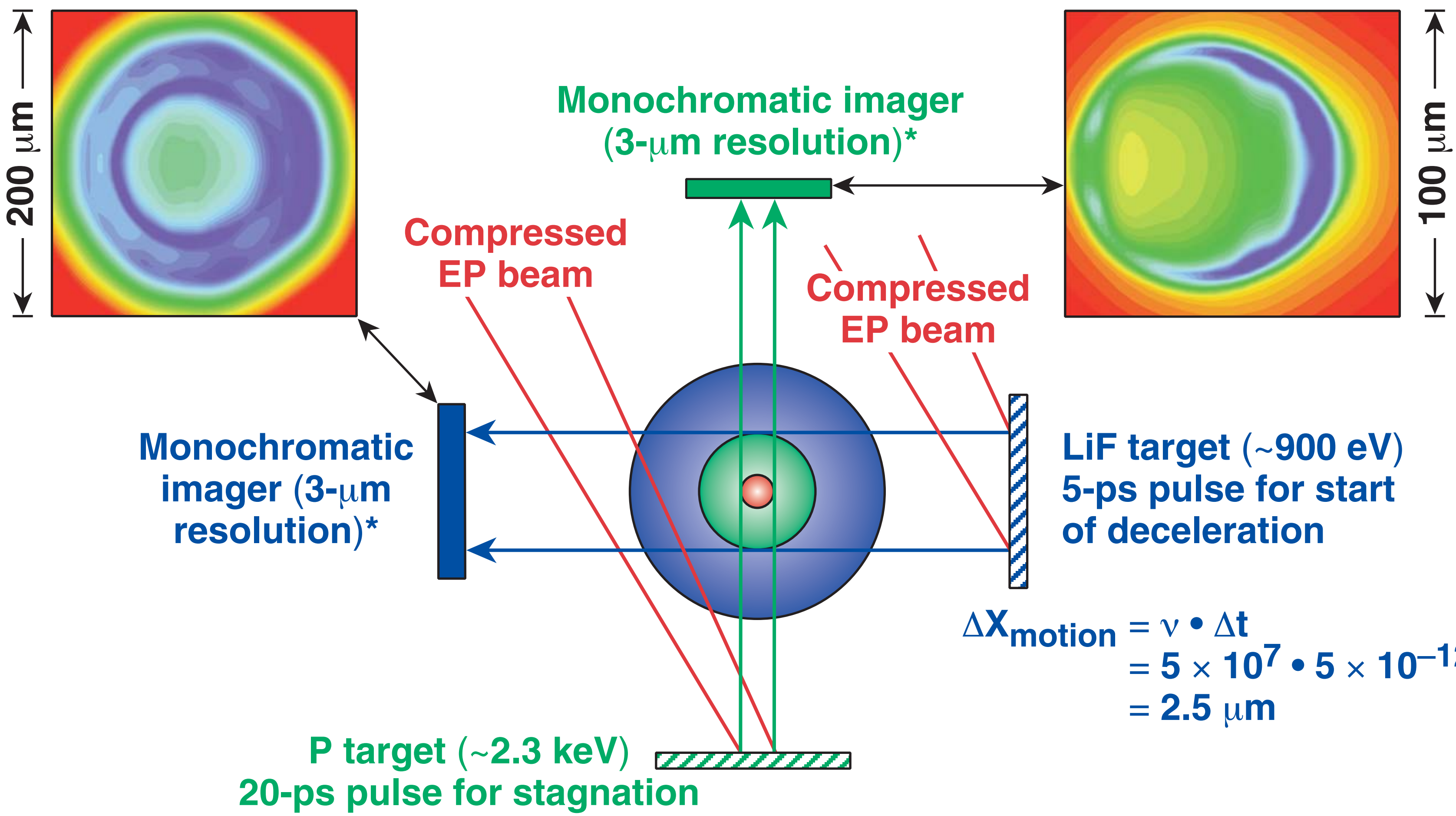


Short-pulse performance	Short-pulse beam 1	Short-pulse beam 2
Short pulse (IR)	1 to 100 ps	35 to 100 ps
IR energy on-target (kJ)	2.6	2.6
Intensity (W/cm^2)	6×10^{20}	$\sim 4 \times 10^{18}$

OMEGA EP will be completed in FY07

G5546r

Core distortions in OMEGA cryogenic implosions can be diagnosed using backlighting techniques and OMEGA EP



$$\Delta X_{motion} = \nu \bullet \Delta t = 5 \times 10^{7} \bullet 5 \times 10^{-12} = 2.5\ \mu m$$

*F. J. Marshall et al., Rev. Sci. Inst. 68, 735 (1997).

OMEGA EP: Fast Ignition

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

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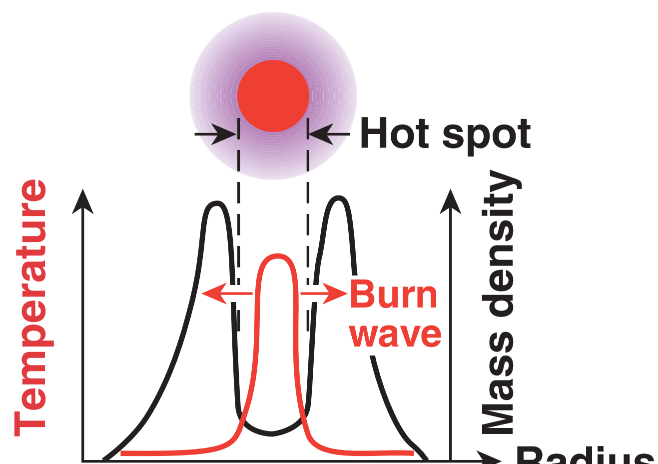
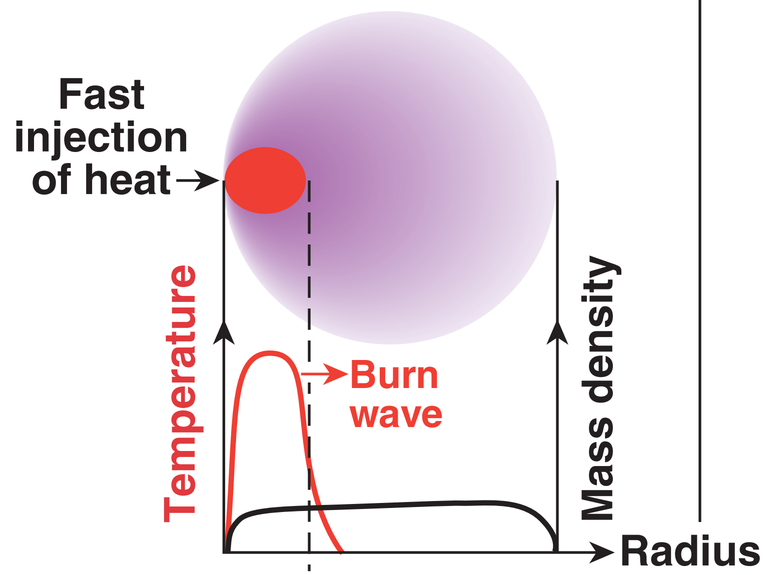
Conventional ICF	Fast Ignitor*
	
Low-density central spot ignites a high-density cold shell	Fast-heated side spot ignites a high-density fuel ball
$\rho T_{hot} \approx \rho T_{cold}$ (isobaric)	$\rho_{hot} \approx \rho_{cold}$ (isochoric)

__Key physics issues__

- hot electron production
- transport to the core
- core formation

E12526d

* M. Tabak *et al.*, Phys. Plasmas 1, 1626 (1994).

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

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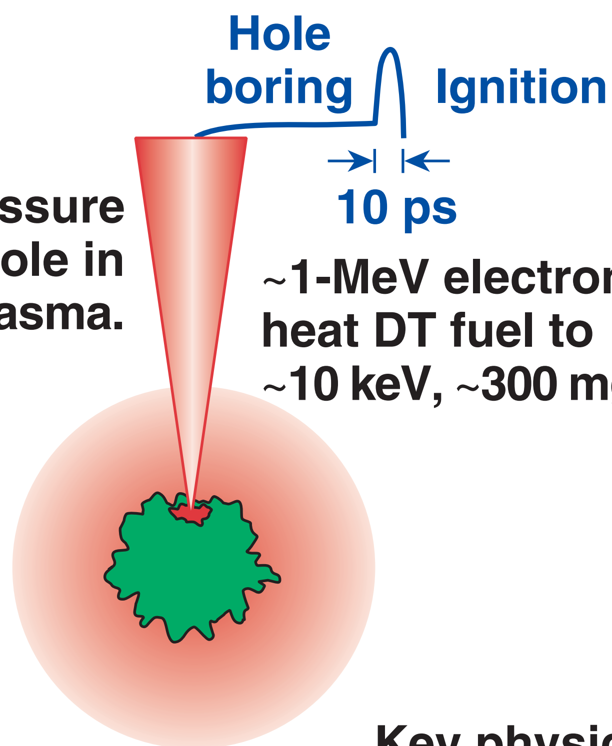
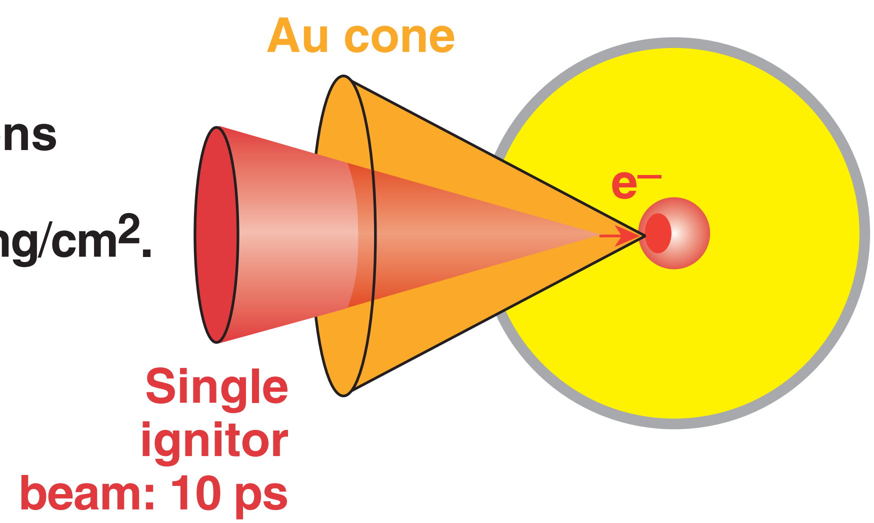
Channeling Concept*



Light pressure bores hole in coronal plasma.

~1-MeV electrons heat DT fuel to ~10 keV, ~300 mg/cm^2.

Cone-Focused Concept**



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* M. Tabak *et al.*, Phys. Plasmas 1, 1626 (1994).
** R. Kodama, Nature 418, 933 (2002).

E11710g

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