The National Direct-Drive Program:
OMEGA to the National Ignition Facility

Pressure threshold for ignition:

\[ P_{hs} = 250 \text{ Gbar} / \sqrt{E_{hs}/10 \text{ kJ}} \]

Current high-foot indirect drive

Required: \(P_{hs} = 350\) to 400 Gbar
Achieved: \(P_{hs} = 226\pm37\) Gbar**

Energy-scaled OMEGA \((E_{hs} = 0.44 \text{ kJ})\)

Required: \(P_{hs} = 140\) Gbar
Achieved: \(P_{hs} = 56\pm7\) Gbar†

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Summary

The goal of the National Direct-Drive Program is to demonstrate and understand the physics of laser direct drive (LDD)

The 100-Gbar Campaign on OMEGA explores the formation of hot-spot conditions relevant for ignition at the 1-MJ scale
- improvements in OMEGA
- improvements in targets
- enhancements in diagnostics
- new modeling and simulation capabilities

The Megajoule Direct Drive (MJDD) Campaign at the National Ignition Facility (NIF) investigates direct-drive physics at long-scale lengths

The 100-Gbar Campaign requires a DT cryogenic fill-tube target.
Collaborators


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The 100-Gbar Campaign on OMEGA and the MJDD Campaign on the NIF are underway to provide a detailed understanding of direct-drive physics.

Spherical direct drive (SDD) on the NIF is the ultimate goal; polar direct drive (PDD) is secondary.
OMEGA DT cryogenic implosions are hydrodynamically scaled from NIF ignition designs

1.5-MJ, spherically symmetric direct-drive design

- \( V_{\text{imp}} = 3.8 \text{ to } 4 \times 10^7 \text{ cm/s} \)
- Adiabat \( \alpha = 1.6 \text{ to } 3 \)
- IFAR\(_{2/3} = 20 \text{ to } 25 \)
- Convergence ratio (CR) = 20 to 23

26- to 29-kJ OMEGA cryogenic design

- \( V_{\text{imp}} \) and IFAR are controlled by varying the ablator (7.5 to 12 \( \mu \text{m} \)) and fuel thickness (40 to 66 \( \mu \text{m} \))

The hot-spot pressure is invariant (100 Gbar on OMEGA = 100 Gbar on the NIF)

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The 100-Gbar Experimental Campaign has nine areas of research

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Improvements to the OMEGA laser are required and ongoing research will refine these needs

80 Gbar (CH ablators)
1. On-target, overlapped laser intensity uniformity over 100 ps of 3% root mean square (rms)

100 Gbar (CH/Si/CH ablators)
1. On-target, overlapped laser intensity uniformity over 100 ps of 1% rms
2. Implementation CBET mitigation technique (spatial, spectral, or temporal)

The on-target, overlapped laser-intensity uniformity depends on the laser power balance and the far-field intensity distribution of each beam on target.
Improvements in targets—development of a fill-tube target—are required and ongoing research will refine these needs

80 Gbar (CH ablators)
1. Target positioned at chamber center to <10 \( \mu m \)
2. Target quality
   a) At shot time, fewer than ten particles in the range of 0.5 to 1.0 \( \mu m \) on the capsule surface and none > 1 \( \mu m \) with heights >0.05 \( \mu m \)
   b) Inner surface roughness of ablator not to exceed \( \sigma_{\text{rms}} = 0.5 \mu m \) in modes \( \ell < 5 \) and \( \sigma_{\text{rms}} = 0.1 \mu m \) in modes \( \ell \geq 5 \)
   c) At cryogenic temperature, determination of the target outer diameter to <2 \( \mu m \)
   d) At cryogenic temperature, determination of target outer surface long wavelength (\( \ell \leq 10 \)) nonuniformity to < 0.1 \( \mu m \)
   e) DT ice-layer thickness known to 0.5 \( \mu m \)
   f) DT ice-layer density known to <5%
   g) Determination of the ablator atomic composition and density (C:H:O:D:T) to <10%
   h) Sphericity TBD

100 Gbar (CH/Si/CH ablators)
1. Target positioned at chamber center to <5 \( \mu m \)
2. Target quality
   a) At shot time, fewer than ten particles in the range of 0.1 to 0.5 \( \mu m \) on the capsule surface and none > 0.5 \( \mu m \) with heights > 0.05 \( \mu m \)
   b) Inner-surface roughness of ablator as 80 Gbar
   c) Target outer diameter as 80 Gbar
   d) Target low-mode nonuniformity as 80 Gbar
   e) DT ice-layer thickness as 80 Gbar
   f) DT ice-layer density as 80 Gbar
   g) Determination of the ablator atomic composition and density (C:H:Si:O:D:T) to <10%; [Si layer added for two-plasmon decay (TPD) mitigation]
   h) Fill tube capability with glue spot <30 \( \mu m \) to fuel CH/Si/CH shells

• CDR for fill-tube target has been completed
• Target metrology workshop defined technique to characterize surface debris
• Delivery date of fill-tube target on OMEGA is Q1 FY20
The DT cryogenic fill-tube target requirement for the 100-Gbar Campaign is based on three factors

1) Nonpermeable ablator materials are required to mitigate laser–plasma interactions
2) Minimizing target debris and defects
3) Minimizing radiation damage to the ablator
Target debris is considered the main seed of short-scale mix

- Simulations include \( \sim 100 \) surface features, size: 1 to 20 \( \mu \text{m} \) in diameter, 0.5 to 1.0 \( \mu \text{m} \) in depth

Characterizing cryogenic targets at the shot time is crucial for understanding target failure mechanisms.
Initial surface features are amplified during shock transit and shell acceleration.

Shocks are launched into the shell.

Shell acceleration

Power (TW)

Time (ns)

Mass-density contours

Shot 55722 glue spot

Shot 55722 glue spot

Local feature

Shocks

Diameter ($d$)

Height ($h$)

Debris particle

$h/d < 0.1$ is ablatively stabilized;

$h/d > 0.1$ is unstable.
Each feature produces a hole in the shell, injecting ablator and cold DT into the vapor region.
Injected mass as a result of instability growth should not significantly exceed the original vapor mass (0.14 µg in OMEGA targets)

- Injected mass from a single feature is \( \sim 4 \times m_0 \sim 10^{-3} \mu g \) for an outer diam (OD) = 5 µm feature
- \( \sim 150 \) to 200 features are sufficient to inject 0.14 µg of cold material into the hot spot
Detailed metrology analysis shows hundreds of micron-scale features on glow discharge polymer (GDP) shells.

Surface features in GDP, \( \sim 300 \) defects

Bright-field microscopy

Polystyrene shells are much smoother (atomic force microscope)

Polystyrene ablators are being explored in current experiments.
A Ge tracer is used to track hydrodynamic mixing of the ablator into the hot spot

Layered DT cryogenic target

- DT ice (50 μm)
- DT vapor
- Ge-doped CH (8 μm, 0.7% atomic)

Mix at stagnation

- Coronal plasma
- Compressed shell
- Hot spot

Time-integrated, spatially resolved Ge Heα + satellite emission from hot spot
(dx = 150 μm*, de = 5 eV)

If Ge reaches the hot spot, it will emit K-shell emission.

* Similar spectrum recorded on same shot with dx = 40 μm and de = 5 eV
XRS: x-ray spectrometer
The hot-spot mix mass inferred from the Ge He$_\alpha$ + satellite emission* will be used to constrain the simulations and refine the target requirements.

Inferred mix-mass quantities:
- $T_e$: 2.5 to 3.9 keV (comparable to $T_i$)
- $n_e$: 2 to 6 $\times$ 10$^{24}$ cm$^{-3}$
- $\rho R_{Ge}$: 0.08 mg/cm$^2$
- Mix mass: 1 to 5 ng

*Similar to NIF hot-spot mix:
Target performance with the fill tube will be examined in FY17

Fill tube with OD = 10 μm (Fill capillary with glue, except for inner 0.1 mm)

Fill tube extends a maximum of 10 to 15 μm inside of the inner plastic ablator wall

DT [50 μm] CH [8.0 μm] with standard OD

Standard stalk-mounted DT cryo target

Fill-tube length = 1.0 mm

45°
The goal of the National Direct-Drive Program is to demonstrate and understand the physics of laser direct drive (LDD).

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  - improvements in OMEGA
  - improvements in targets
  - enhancements in diagnostics
  - new modeling and simulation capabilities

- The Megajoule Direct Drive (MJDD) Campaign at the National Ignition Facility (NIF) investigates direct-drive physics at long-scale lengths.

The 100-Gbar Campaign requires a DT cryogenic fill-tube target.
Backup
A major advantage of direct drive over indirect drive is the increased coupled energy to the hot spot and relaxed hot-spot requirements.

- **Pressure threshold for ignition†**
  \[ P_{hs} = 250 \text{ Gbar} \div \sqrt{E_{hs}/10 \text{ kJ}} \]

- **Generalized Lawson criterion***
  \[ \chi_{no} \alpha = \frac{P \tau}{P \tau_{ign}} = \left( \rho R_{no} \alpha \right)^{0.61} \left( 0.12 Y_{no}^{16} / M_{DT}^{stag} \right)^{0.34} \]

- **Energy scaling***,†
  \[ \left( \frac{E_{NIF}}{E_{OMEGA}} \right)^{0.35} \]

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Current high-foot indirect drive*
Required: \( P_{hs} = 350 \text{ to } 400 \text{ Gbar} \)
Achieved: \( P_{hs} = 226 \pm 37 \text{ Gbar} \)
\( \chi_{no} \alpha = 0.66^{***} \)

Energy-scaled OMEGA (\( E_{hs} = 0.44 \text{ kJ} \))†
Required: \( P_{hs} = 140 \text{ Gbar} \)
Achieved: \( P_{hs} = 56 \pm 7 \text{ Gbar} \)
\( \chi_{no} \alpha \) (energy scaled‡) = 0.64†

Direct-drive ignition:
CR ≥ 22 and \( P_{hs} > 120 \text{ Gbar} \)

Indirect-drive ignition:
CR = 30 to 40 and \( P_{hs} > 350 \text{ Gbar} \)

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The 100-Gbar program has 80 Gbar as a first near-term goal

- System requirements are less demanding for 80 Gbar
  - power balance ~3% rms
  - target placement <10 μm
  - target quality (debris level)
- CBET mitigation and multilayer ablators are not required for 80 Gbar
  - CH, CD ablators will be used
  - laser upgrades for CBET mitigation should proceed in parallel
  - multilayered ablators (Si) for TPD control should proceed in parallel
- “Touchstone” for physics/simulations

The approach is to fix the laser-drive nonuniformity first, then mitigate CBET.
Long wavelength perturbations limit the hot-spot pressure on OMEGA; short wavelength perturbations affect low-adiabat implosions

Generalized Lawson criterion

\[ \chi_{\text{scaled}} = \frac{P\tau}{P\tau_{\text{ign}}} = (\rho R_{\text{no}} \alpha)^{0.61} \left( \frac{0.12 Y_{\text{no}}^{16} \alpha}{M_{\text{stag}}^{\text{DT}}} \right)^{0.34} \left( \frac{E_{\text{NIF}}}{E_{\text{laser}}} \right)^{0.35} \]

Fuel adiabat

\[ \alpha = P/P_{\text{Fermi}} \]

- High-adiabat implosions (\( \alpha \sim 7 \)) are being investigated for the 1-D physics campaign.


A feature with $a_0 \sim 0.1 \, \mu m$ and $d \sim 5 \, \mu m$ becomes nonlinear at the onset of acceleration.

\[ \frac{a}{d} < 0.1 \text{ ablatively stabilized} \]

\[ \frac{a}{d} > 0.1 \text{ unstable} \]
General Atomics measures the low-mode surface roughness with the atomic-force microscopy sphere mapper.

The low-mode surface roughness target specification is being generated using multidimensional hydrodynamic simulations.