Early time

Laser drive

Shock timing (EOS)

Stopping power determines $\alpha$ heating

Peak compression

Laser Direct-Drive Inertial Confinement Fusion

Acceleration phase

EOS/opacity/$\kappa$ determines $\rho$–$T$ conditions

Deceleration phase

$L\alpha$ determines ablation in the hot spot

S. P. Regan
University of Rochester
Laboratory for Laser Energetics

Nuclear Photonics 2018
Brasov, Romania
25–29 June 2018
The 100-Gbar Campaign on OMEGA explores the formation of hot-spot conditions relevant for ignition at the megajoule scale for laser direct drive (LDD)

- The enhanced-capability approach fixes long-/short-wavelength perturbations, mitigates laser–plasma instabilities (LPI), and improves energy coupling to increase yield ($Y$) and areal density ($\rho R$)
- The statistical approach uses existing capabilities to find the optimum implosion
- The Megajoule Direct-Drive (MJDD) Campaign at the National Ignition Facility (NIF) investigates direct-drive physics at long scale lengths

2020 goal: demonstrate and understand an increase in $Y$ and $\rho R$

$[P_{hs} = 80 \text{ Gbar}, \text{energy scaled } (\chi_{\text{no } \alpha})_{\text{scaled}} = 0.8 \text{ to } 0.85]^*$

2023 goal: define LDD requirements to achieve ignition-relevant $P_{hs} \geq 100 \text{ Gbar}$

$[\text{energy scaled } (\chi_{\text{no } \alpha})_{\text{scaled}} = 0.95 \text{ to } 0.98]^*$

*scaled to $E_{UV} = 1.9 \text{ MJ}$
Collaborations

University of Rochester
Laboratory for Laser Energetics

Lawrence Livermore National Laboratory

Naval Research Laboratory

Belcan Corporation

General Atomics

Plasma Science and Fusion Center, MIT

Los Alamos National Laboratory
The National Direct-Drive Program includes OMEGA and NIF experiments to study direct-drive target physics.

**National Direct-Drive ICF Program**

**OMEGA**
- 30 kJ
- 60 beam
- 351 nm

**NIF**
- 1.8 MJ
- 192 beam
- 351 nm

**Scale 1:70 in energy**

**OMEGA 26 kJ**

**NIF 1.8 MJ**

**3.6 mm**

**0.86 mm**

**Laser coupling, preheat, imprint, and hydrodynamically scaled implosions.**

**Laser coupling, preheat, and imprint at the MJ scale.**
Ignition (gain = 1) laser direct drive (LDD) requires a hot-spot pressure above 120 Gbar and a convergence ratio above 22.

Laser indirect drive (LID) has demonstrated it is possible to achieve a hot-spot pressure above 300 Gbar.*

CBET: cross-beam energy transfer

*P. K. Patel, Lawrence Livermore National Laboratory, private communication (2017);
O. A. Hurricane et al., Nature 506, 343 (2014);
Direct-drive laser–plasma interaction (LPI) includes CBET,* stimulated Raman scattering (SRS), and two-plasmon–decay (TPD) instability

• The interaction of crossed laser beams with an expanding plasma causes CBET (seeded Brillouin scattering) between beams

• CBET mitigation strategies
  – spatial (beam zooming, $R_{\text{beam}}/R_{\text{target}} < 1$)
  – spectral (wavelength detuning, high bandwidth)
  – temporal (modulated laser pulse)

• TPD is expected to increase on OMEGA when CBET is reduced (intensity at $n_c/4$ will increase)
  – TPD mitigation: modify plasma conditions using multilayer (CH/Si/CHSi) ablators

• LPI scaling from OMEGA to ignition-scale coronal plasma
  – NIF experiments are performed at longer scale lengths and higher temperatures than OMEGA
  – SRS appears to dominate TPD in an ignition-scale coronal plasma; mitigation techniques are being developed/evaluated

---

CBET reduces $P_{abl}$ on OMEGA by 40%; a spatial mitigation technique has been demonstrated on OMEGA.

$$P_{hs} \sim P_{abl}^{1/3} V_{imp}^{10/3} / \alpha$$

$$P_{hs} \sim P_{abl}^{1/3} \text{IFAR}^{5/3}$$

$$\alpha = \frac{P}{P_{Fermi}}$$

1-D (beam size = 820 $\mu$m)
1-D (beam size = target size)

Increase caused by CBET reduction

Increase in density scale length

Long-wavelength perturbations limit the hot-spot pressure on OMEGA; short-wavelength perturbations affect low-adiabat implosions.

Generalized Lawson criterion**

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

Long wavelengths (debris, imprint)

Short wavelengths (drive, offset)

1-D simulations

Simulations with mitigated CBET

Experiment†

Long wavelengths

Experiment†

Fuel adiabat

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

Shot with inferred \( P_{\text{hs}} > 50 \) Gbar


** R. Betti et al., Phys. Rev. Lett. 114, 255003 (2015);

The physics goals and the laser and target requirements are derived from ignition target designs at the MJ NIF energy scale.

**Target-design parameters**

\[ V_{\text{imp}} = 3.5 \text{ to } 5.0 \times 10^7 \text{ cm/s} \]
\[ \alpha = 2.5 \text{ to } 7.0 \]
\[ \text{CR}^* = 10 \text{ to } 23 \]
\[ \text{IFAR}^{**} = 15 \text{ to } 20 \]

\[ \alpha = \frac{P}{P_F} \]
\[ \text{IFAR} = \frac{\text{shell radius}}{\text{shell thickness}} \]

OMEGA implosions are hydrodynamically scaled from the NIF direct-drive ignition design (radius \(\sim\) laser energy\(^{1/3}\), time \(\sim\) laser energy\(^{1/3}\), laser power \(\sim\) laser energy\(^{2/3}\)).

---

*CR: convergence ratio


IFAR: in-flight aspect ratio
**100-Gbar Campaign**

The enhanced-capability approach has an 80-Gbar 2020 goal

- System requirements are less demanding for 80 Gbar compared to 100 Gbar
  - on-target, overlapped intensity 1% rms (beam-to-beam intensity balance of 3% rms)
  - target placement accuracy <10 µm
  - target quality less stringent (debris level)
- CBET reduction using spatial technique of R75 phase plate \( \frac{R_b}{R_t} = 0.75 \) will be implemented
  - delivery date of 60 R75 phase plates is the end of FY18
- GDP* and PS** ablators will be needed for 80 Gbar

---

*GDP: glow-discharge polymer  
**PS: polystyrene  
Improvements to the OMEGA laser and target positioning are required to reduce the level of laser-drive nonuniformity

**Laser-drive nonuniformity 80 Gbar (CH ablators)**
1. On-target, overlapped intensity averaged over 100 ps of 1% rms (beam-to-beam balance of 3% rms)
2. Implement spatial CBET mitigation technique (R75 phase plate)

**100 Gbar (multilayered ablators)**
1. Same as 80 Gbar or better
2. Implement spatial and spectral CBET mitigation technique (R75 with $\Delta \lambda = \pm 3 \text{ Å}$ with reduced energy)

**Target-positioning requirements: target offset = $\Delta R < 5 \text{ µm}$**

On-target, laser-drive diagnostics (UV and x ray) are being developed.

---

*100-Gbar Campaign*

---

$^*$TCC: target chamber center
OMEGA is being diagnosed—gains, losses, frequency conversion, near fields, and far fields—to improve the laser power balance.

Current power-balance measurements (recorded near the frequency-conversion crystals)

On-target measurements are needed to diagnose the laser drive.
Proof-of-principle experiments on warm implosions demonstrated subpercent-scale control of low modes with 3-D gated x-ray imaging*

Three-dimensional effects of the laser-drive nonuniformity will be applied to DT cryogenic implosions.

---

100-Gbar Campaign

The DT cryogenic fill-tube target requirement for the 100-Gbar Campaign is based on three factors:

1. Nonpermeable capsules are needed to optimize ablator and laser–plasma interaction mitigation*
2. Minimizing target debris and defects (80- and 100-Gbar specs)
3. Minimizing radiation damage to the ablator

Glass fill tube (10 μm) inserted into a 150-μm polymicro™ tube

First fill-tube target on OMEGA: Q1 FY20

Nonpermeable multilayer ablator

- 4 μm CHSi (6%)
- 0.5 to 1 μm mid-Z
- 3 μm CH
- 45 μm DT

Effects of engineering features (e.g., fill tube, stalk, debris, vacuoles) on target performance are being examined.

Polystyrene ablators are being developed to meet the target specification for surface features (based on hydrodynamic simulations*)

Atomic force microscopy measurements of GDP and PS ablators

The 100-Gbar Campaign can tolerate a limited number of features above the black curve.*

---

A target-physics platform has been developed to study the effects of ablator material mixing into the hot spot at stagnation (hot-spot mix)*

Controlled experiments will be performed to understand the seeds (e.g., engineering features, microscopic debris, laser imprint).

*Similar to NIF hot-spot mix:

XRS: x-ray spectrometer
$\alpha$: adiabat = $P/P_{\text{Fermi}}$

Monochromatic backlighting of the DT compressed shell is being extended from CR \( \sim 10^{10} \) to stagnation.

In progress:

1. Improve spatial resolution from 15 \( \mu \text{m} \) to <5 \( \mu \text{m} \)
   - work with crystal vendors to improve quality of bent crystals
   - efforts at NIF, OMEGA, and Z influence one another

2. Develop brighter x-ray backlighters

---

**100-Gbar Campaign**

*C. Stoeckl et al., Phys. Plasmas 24, 056304 (2017).*
X-ray and nuclear diagnostics are being developed* to study the multidimensional effects of hot-spot formation and stagnation

- **3-D measurements**
  - gated x-ray imaging of hot spot (<5-µm spatial, ~10-ps temporal resolution) and disassembly
  - neutron time of flight ($T_i$, $\rho R$, $T_i$ and $\rho R$ asymmetry, residual kinetic energy, DD-n and DT-n yields)
  - $\rho R(\theta, \phi)$ diagnostic for higher-order spatial variations

- Probing the compressed fuel layer using 2-keV x-ray backlighting and Compton radiography

- Absolute time- and space-resolved hot-spot x-ray continuum measurement to infer $T_e$, $\rho R$, and hot-spot mix mass
  - compare $T_e$ (x ray) with $T_i$ (nTOF) of hot spot

---

*In collaboration with the National Diagnostics Working Group*
100-Gbar Campaign

The statistical approach uses existing capabilities to find the optimum implosion

Statistical approach

Hydro-stability or laser-energy boundary

Optimum implosion

Increase DT thickness

Optimization campaign

Velocity campaign

Larger yield by increasing OD, better coupling, larger V_{imp}, larger IFAR

TC14102a

Measured $Y = 1.17 \times 10^{14}$ and $\rho R = 165 \text{ mg/cm}^2$ were achieved; FY18/FY19 goal is to maintain the Y and increase $\rho R$ to 200 mg/cm$^2$.

Path #1 start point: high-adiabat, low CR

Path #2 start point: low-adiabat, high CR

04/04/18: $Y = 1.17 (\pm 0.06) \times 10^{14}$ $\rho R = 165 (\pm 0.23) \text{ mg/cm}^2$
03/06/18: $Y = 1.03 \times 10^{14}$ $\rho R = 135 \text{ mg/cm}^2$
01/16/18: $Y = 1.28 \times 10^{14}$ $\rho R = 127 \text{ mg/cm}^2$
10/03/17: $Y = 1.37 \times 10^{14}$ $\rho R = 100 \text{ mg/cm}^2$

$\langle \chi_{\text{no } \alpha} \rangle_{\text{scaled}} = 0.7^*$

$^*$Scaled to $E_{UV} = 1.9 \text{ MJ}$
100-Gbar Campaign

The combination of 1-D simulations and mapping relations provides a predictive capability as long as its validity can be extrapolated.
Research at LLE will explore concepts for mitigating laser–plasma instabilities in direct-drive implosions that include spatial, temporal (bandwidth), and spectral (wavelength detuning) techniques.

LPI research must again be a focus of inertial fusion and high-energy-density–physics research.
CBET experiments will be performed on OMEGA starting in June 2018.

Laser upgrades on OMEGA for LPI mitigation are being explored.

*FCC: frequency conversion crystal*
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[energy scaled ($\chi_{no \alpha}$)scaled = 0.95 to 0.98] **

*scaled to $E_{UV} = 1.9$ MJ
Backup
A Preliminary Design Review for the DT cryogenic fill-tube target* is planned for Sept. 2018 and the first fill-tube target will be fielded on OMEGA in Q1 FY20.

Cryostat design validated in test facility (DT cryo target supported with 10-μm OD fill tube achieved 0.9-μm rms DT ice layer)

Prototype fill-tube target

Structural design on H5 port on OMEGA

Cryostat design validated in test facility

Linear motor

Deformable region of the shroud

Target

“Port hole”

10-μm OD fill tube

860-μm OD capsule

3 mm

DT cryo target with fill tube 860-μm OD

Cold finger and fill tube

Helium

OMEGA structural steel

Characterization chamber

Cryocooler

PS capsules and advanced imaging diagnostics are being developed to meet the specifications for microscopic surface features on target at shot time.

25-Gbar Campaign

X-ray phase contrast image (used to characterize layer quality)

** OD: outside diameter
The single line-of-sight time-resolved x-ray imager was fielded on OMEGA* to provide a second line of sight (LOS) to diagnose the hot spot.

The KBFramed** imager provides the first LOS; planning for a third LOS is underway.

---

*CMOS: complementary metal oxide semiconductor


First implosion images of a DT cryogenic implosion with SLOS-TRXI provided LDD data on the hot-spot formation and stagnation.

The next phase of SLOS-TRXI is to improve the spatial resolution (< 5 μm) using a Kirkpatrick–Baez microscope, penumbral imaging, or toroidal x-ray imager.

Multidimensional effects of hot-spot formation will be studied with 3-D gated x-ray imaging.
The second of three orthogonal shielded and collimated LOS’s for nToF detectors is being implemented on OMEGA.

**Goal:** Have 3-D shielded, collimated LOS’s for nToF detectors

- DD-n and DT-n yield and ion temperature (residual kinetic energy)
- Compressed fuel areal density (spatial variations)

**Mechanical drawings of three LOS for nTOF**

<table>
<thead>
<tr>
<th></th>
<th>P2</th>
<th>P7</th>
<th>H10</th>
</tr>
</thead>
<tbody>
<tr>
<td>P2</td>
<td>0°</td>
<td>122.3°</td>
<td>97.2°</td>
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<tr>
<td>P7</td>
<td>122.3°</td>
<td>0°</td>
<td>139.6°</td>
</tr>
<tr>
<td>H10</td>
<td>97.2°</td>
<td>139.6°</td>
<td>0°</td>
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</table>
The hot-spot $T_e$ will be diagnosed this summer using x-ray continuum emission.

**NIF Continuum Spectrometer**
- Conical Bragg crystal
- 20 to 30 keV

**NIF ConSpec in OMEGA TIM**

Goal: time- and space-resolved x-ray continuum spectral measurement to infer hot-spot $T_e$ and absolute radiation (hot-spot mix), and compressed areal density of the shell.

- Compare $T_e$ (X ray) and $T_i$ (nTOF) of hot spot

---

Accurate knowledge of DT and ablator properties [equation of state (EOS), opacity, conductivity ($\kappa$), and stopping power] is required for ICF simulations.

Early time
- Laser drive
- Shock timing (EOS)
- Stopping power determines $\alpha$ heating

Acceleration phase
- Laser drive
- EOS/opacity/$\kappa$ determines $\rho$–$T$ conditions

Peak compression
- DT gas

Deceleration phase
- Laser drive
- $\kappa$ determines ablation in the hot spot

First-Principles Computations (QMD*, PIMC**) are used in LILAC and DRACO

CH: EOS,$^1$ opacity,$^2$ conductivity,$^3$
DT: EOS,$^4$ opacity,$^5$ conductivity$^6$


The microphysics models used in hydrodynamics codes are being improved through experiments and first-principles computations.

*QMD = quantum molecular dynamics
**PIMC = path-integral Monte Carlo
The MJDD Campaign on the NIF studies energy coupling, laser imprint, and LPI's for ignition-scale coronal plasmas

**Planar LPI planar imprint**

**Cone-in-shell shock timing/imprint**

**Implosions**

**NIF platforms**

**Hot-electron generation and CBET mitigation experiments on the NIF are highlighted.**

*VISAR: velocity interferometer system for any reflector
Origins and scaling of hot-electron preheat in ignition-scale direct-drive ICF experiments are investigated on the NIF*

**Scattered-light measurements from planar targets**, **

**Collection angle from target normal**

0°

OMEGA spherical experiment

<table>
<thead>
<tr>
<th>Collection angle from target normal</th>
<th>Scattered-light spectrum</th>
<th>Total laser power</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>0°</td>
<td>0°</td>
</tr>
<tr>
<td>23.5°</td>
<td>23.5°</td>
<td>23.5°</td>
</tr>
<tr>
<td>50°</td>
<td>50°</td>
<td>50°</td>
</tr>
</tbody>
</table>

**Experimental geometry and laser pulse**

**Fraction of laser energy converted to hot electrons**

**NIF**: $L_n = 525 \, \mu m$

$T_e = 4.5 \, keV$

**OMEGA**: $L_n = 150 \, \mu m$

$T_e = 2.8 \, keV$


**W. Seka et al., Phys. Plasmas 16, 052701 (2009)."
Spatial and spectral CBET mitigation strategies have been demonstrated on OMEGA and the NIF.
Laser–plasma Interaction physics and corona conditions for laser direct drive at the MJ energy scale

- Direct-drive parameters (ignition scale at $n_c/4$)
  - density scale length, $L_n \sim 500 \mu m$ to 600 $\mu m$
  - electron temperature, $T_e \sim 4$ to 5 keV
  - summed laser intensity, $I_\Sigma = 6$ to $10 \times 10^{14}$ W/cm$^2$ on target, 3 to $5 \times 10^{14}$ at $n_c/4$
    - single-beam intensity, $I_s \sim 3$ to $10 \times 10^{13}$ W/cm$^2$

Understanding LPI impacts all laser-based ICF/HEDP† approaches.
The intensity-driven laser–plasma instabilities that reduce absorption, ablation pressure, or increase the imploding shell adiabat place additional challenges on capsule hydrodynamics or driver energy

- **Target absorption** ($E_{hs}$)
  - required central region hot-spot pressure ($P_{hs}$) from generalized Lawson parameter for ignition
    - $P_{hs} > 250$ Gbar ($E_{hs}/10$ kJ)$^{-1/2}$

- **Ablation pressure** ($P_{abl}$)
  - trade-off with hydrodynamic stability with in-flight-aspect ratio ($\text{IFAR} = R/\Delta R$) as a metric
    - $P_{hs} \sim P_{abl} (\text{IFAR})^{5/3}$

- **Adiabat** ($\alpha$)
  - entropy of the imploding shell determined by $\alpha (P_{shell}/P_{Fermi})$, $V_{imp}$ is the capsule implosion velocity
  - adiabat is determined by shock history and preheat
    - $P_{hs} \sim (P_{abl})^{1/3} (V_{imp})^{3} (\alpha)^{-1}$
Coronal conditions at megajoule-scale facilities are significantly different from OMEGA (tens of kJ) scale

2-D DRACO simulated plasma and laser conditions at $n_c/4$

<table>
<thead>
<tr>
<th></th>
<th>NIF ignition scale</th>
<th>Ongoing NIF planar experiments</th>
<th>Ongoing NIF implosions</th>
<th>OMEGA experiments</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_n$ ($\mu$m)</td>
<td>600</td>
<td>400 to 700</td>
<td>360</td>
<td>150</td>
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<tr>
<td>$T_e$ (keV)</td>
<td>3.5 to 5.0</td>
<td>3.0 to 5.0</td>
<td>3.2</td>
<td>2.8</td>
</tr>
<tr>
<td>$I_L$ (W/cm$^2$)</td>
<td>(6 to 8) $\times 10^{14}$</td>
<td>(6 to 15) $\times 10^{14}$</td>
<td>$5 \times 10^{14}$</td>
<td>(5 to 7) $\times 10^{14}$</td>
</tr>
</tbody>
</table>
The interaction of crossed laser beams within an expanding plasma causes CBET between beams

- This stimulated Brillouin scattering (SBS)-based interaction leads to a resonance condition for transferring energy between a pump ray and a probe ray by means of an ion-acoustic wave $k_a^*$

\[
\eta = \frac{(\omega_{\text{pump}} - \omega_{\text{probe}}) - k_a \cdot v_{\text{fluid}}}{k_a |c_a|}
\]

- The resonance condition peaks when the matching condition is met

\[
\eta > 0; \text{ gain} \\
\eta < 0; \text{ loss}
\]

Resonance ($\pm 1$) occurs in the neighborhood of the Mach-1 surface under typical conditions.