Initial integrated fast-ignition results with a 1-kJ, 10-ps OMEGA EP beam

Neutron yield ($\times 10^7$)

OMEGA EP arrival time (ns)

- Integrated FI shots
- Average without short pulse
OMEGA EP is routinely delivering the world’s highest short-pulse energy

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  - a new operating limit of 1.5 kJ in a 10-ps pulse was determined
- New laser and target diagnostics are continually being added
  - 83 target diagnostics qualified
  - a single-shot contrast diagnostic is being installed
- Initial experiments show promising results
  - many external users
  - fast-electron coupling independent of pulse duration and energy
  - initial fast-ignition experiments have doubled the neutron yield

OMEGA EP’s first year as a user facility has been successful—350 shots with 30 PI’s.
Collaborators


Laboratory for Laser Energetics
University of Rochester
OMEGA EP beamlines can be operated as short-pulse high-energy petawatt at 1.0 μm or long-pulse at 0.35 μm.

<table>
<thead>
<tr>
<th>Performance capabilities</th>
<th>Short-pulse Beam 1</th>
<th>Short-pulse Beam 2</th>
<th>Long pulse (any beam)</th>
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</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>Infrared (1.0 μm)</td>
<td>Infrared (1.0 μm)</td>
<td>UV (0.35 μm)</td>
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<tr>
<td>Pulse width</td>
<td>1 to 100 ps</td>
<td>1 to 100 ps</td>
<td>1 ns</td>
</tr>
<tr>
<td>Energy on target (kJ)</td>
<td>2.6 kJ, 10–100 ps</td>
<td>2.6 kJ, 80–100 ps</td>
<td>2.5</td>
</tr>
<tr>
<td>grating limited &lt;10 ps</td>
<td>beam combiner limited &lt;80 ps</td>
<td></td>
<td>6.5</td>
</tr>
<tr>
<td>Intensity (W/cm²)</td>
<td>3 × 10²⁰</td>
<td>∼2 × 10¹⁸</td>
<td>3 × 10¹⁶</td>
</tr>
<tr>
<td>Focusing (diam)</td>
<td>&gt;80% in 20 μm</td>
<td>&gt;80% in 40 μm</td>
<td>&gt;80% in 100 μm</td>
</tr>
</tbody>
</table>

Short-pulse beams can be directed either to OMEGA or to the OMEGA EP target chamber.
LLE is in the process of obtaining a set of higher damage-threshold UV optics

- LLNL is an essential partner in producing high-damage-threshold UV optics and processing them for maximum fluence

### UV Optics Acquisition

<table>
<thead>
<tr>
<th>ITEM</th>
<th>FY09</th>
<th>FY10</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 – Focus Lenses</td>
<td></td>
<td></td>
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<tr>
<td>5 – Vacuum Windows</td>
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<td></td>
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<td>5 – UV Diagnostic Beamsplitters</td>
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<tr>
<td>Distributed phase plate imprinting (qty 2)</td>
<td></td>
<td></td>
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<tr>
<td>Distributed phase plate substrate (qty 4)</td>
<td></td>
<td></td>
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<td>Distributed phase plate imprinting (qty 4)</td>
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</tbody>
</table>

#### Timeline:
- **Contract placed with vendor**
- **Vendor production**
- **LLNL UV optic processing and shipment**
- **Installed and ready for high-power use**
The UV energy is limited by optic damage threshold.

- LLNL is managing the procurement of replacement optics for OMEGA EP.
- Bulk fused-silica inclusions and surface-finish quality limits UV laser-damage threshold (LDT) of initial optics.
- LLNL procedures, quality control, and processing are required to achieve high LDT’s.
The first two OMEGA EP DPP’s are available for use in FY10

- UV drive uniformity is increased on OMEGA EP by the addition of DPP’s
- Reduced-correlation design using improved simulated annealing technique gives high uniformity in low–mid spatial frequencies

**OMEGA EP DPP**

430 × 430 mm

Phase pattern shown is imprinted on a fused silica optic by magnetorheological finishing
The DPP profile at best focus on OMEGA EP is an eighth-order super-Gaussian 750-\(\mu\)m spot.

Geometrical through-focus (\(\pm 15\) mm)

Normalized irradiance

Far-field intensity in terms of averaged intensity over the flat-top area

375-\(\mu\)m half width at half maximum

The next three phase plates will have 550-\(\mu\)m HWHM.
The FY10 short-pulse (IR) operating envelope is constrained by optics damage and the $B$-integral of the disposable debris shield (DDS)

A test energy ramp in September 2009 assessed an expanded operational envelope—2.1 kJ on target.
The backlighter ramp to 2.1 kJ showed significant optics damage.

From the rest of the compressor, the damage grew with subsequent 1.5-kJ, 10-ps shots.

Approximately 1% of the surface area was damaged.
OMEGA EP short-pulse capability will be ramped to 1.5 kJ on-target in 10 ps by February 2010

- The four damaged optics are being replaced
- Damage-free operation at 1 kJ 10 ps will be available immediately
- The system will be ramped to 1.5 kJ, 10 ps during Q1FY10 and the first part of Q2 campaigns with extensive pre- and post-campaign inspections

Work to understand the damage will continue with the goal of providing 2.6 kJ in the future.
The OMEGA EP short-pulse focal spot continues to improve with $R_{80} < 25 \, \mu m$ demonstrated.

![Graph showing encircled energy and on-target intensity](image.png)
The OMEGA EP on-shot contrast diagnostics will be deployed in Q1FY10

- The on-shot OMEGA EP contrast will be measured with two diagnostics
  - fast diode and scope
    - up to ~0.5 ns before the pulse, 80-dB dynamic range
    - currently installed in a temporary location
  - single-shot cross-correlator
    - 0.5 ns before the peak-to-peak, 80 ~ 100-dB dynamic range

Contrast to 0.5 ns before the peak with 1.5-kJ, 10-ps pulse duration relative to 10-ps pulse

The pedestal contains approximately $10^{-4}$ of the main pulse energy (~150 mJ).
A single-shot, third-order cross-correlator based on an optical pulse replicator will be deployed*.

1. 1\(\omega\) pulse intensity is obtained by nonlinear interaction with a sequence of 2\(\omega\) sampling pulses generated by a pulse replicator.
2. Sensitivity adjusted for different temporal ranges using neutral density filters after the pulse replicator.
3. Background-free detection at 3\(\omega\) for high-dynamic-range (80 to 100 dB) measurements from 500 ps before the peak.

Backlit images of cryogenic targets are captured by a soft x-ray framing camera.

- Ir-coated mirrors significantly reduce the hard x-ray background by reflecting x rays below 2 keV.
X-ray radiography is used to infer target areal density during a cryogenic implosion.

The backlit image was Abel inverted.

$\rho^2 R$ of $\sim 0.097 \text{ g}^2/\text{cm}^5$ was inferred from the optical depth.

A $\rho R$ of $\sim 33 \text{ mg/cm}^2$ was inferred using the radius of the measured image of $\Delta R \sim 110 \mu \text{m}$ and an ice-block model.

This image was well before peak compression.
The diameter of the shell radiograph and the inferred $\rho R$ are consistent with simulated values at a time well before peak compression.

- Measured shell radius = 140 $\mu$m
- Experimentally inferred $\rho R = 33$ mg/cm$^2$
Fast-electron recirculation in mass-limited targets allows access to high-energy-density phenomena

- Refluxing is caused by Debye-sheath field effects
- Majority of fast electrons are stopped in the target
- Provides a simple geometry for testing laser-coupling, electron-generation, and target-heating models

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K-photon radiation reveals hot-electron production and bulk heating of small-mass targets*

- Intense laser–plasma interaction produces energetic electrons that leave K-shell vacancies
- $K_{\alpha}$ yield indicates hot-electron conversion efficiency
- Inelastic collisions heat the target and ionize outer shell electrons
- Collisional ionization with thermal background plasma occurs
- $T_e > 100$ eV causes significant M-shell depletion, which affects $K_{\beta}$ yield
- Target heating is inferred from $K_{\beta}/K_{\alpha}$

K-photon emission-suppression measurements were performed on OMEGA EP using up to 2.1-kJ, 12-ps pulses

- Similar K-photon emission characteristics are observed using 1-ps MTW pulses and 10-ps OMEGA EP pulses
- The laser-energy conversion efficiency into fast electrons is independent of the laser pulse duration ($\tau_p \leq 12$ ps)

The inferred laser-to-hot-electron conversion efficiency is $\sim 20\%$ and constant for 1-J, 1-ps to 2.1-kJ, 12-ps laser pulses.

Integrated fast-ignition experiments have begun on the Omega Laser Facility

• LLE has begun integrated cone-in-shell fast-ignition experiments with warm CD shells

• Initial experiments showed an increase in x-ray emission for the cone tip, but x-ray and γ background blinded neutron diagnostics

• A new liquid scintillator detector was developed that makes it possible to measure neutron yield with the OMEGA EP laser beam*

• Approximately 1 kJ of a 10-ps OMEGA EP laser pulse was incident on a compressed target

A neutron time-of-flight detector with a liquid scintillator showed no long decay tail from an intense hard x-ray pulse.

This scintillator is used in FI experiments to measure the $D_2$ neutron yield.
The neutron yield increased a factor of two with an appropriately timed OMEGA EP beam.

1.7 ± 0.5 \times 10^7 additional neutrons were produced with the short-pulse laser.
An integrated fast-ignition simulation\(^1\) capability combining the hydrocode **DRACO**\(^2\) with the particle code **LSP**\(^3\) reproduces the experimental results

- **DRACO**\(^2\) is a 2-D cylindrically symmetric hydrodynamic code that includes the necessary physics for ignition and burn of the imploded capsules
- **LSP**\(^3\) is a 2-D/3-D implicit-hybrid PIC code
- Simulations show good agreement with the measured neutron yields with 1 kJ of OMEGA EP laser energy with 10% laser fast-electron conversion efficiency

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Summary/Conclusions

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