Fast-Ignition Integrated Experiments on OMEGA

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Summary

Integrated experiments study the coupling of fast electron energy into a compressed core

- The short-pulse laser produced up to $1.5 \pm 0.5 \times 10^7$ additional neutrons with proper beam timing
- Shock breakout measurements confirm an intact cone tip at the neutron peak, showing that the neutron yield is due fast electron coupling
- 20 MeV electrons are measured in the laser forward direction, indicating that the pre-plasma plays an important role in the interaction
- DRACO-LSP integrated simulations model target implosion and heating and indicate a better coupling at higher laser intensity
Collaborators


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Integrated fast-ignition experiments with re-entrant cone targets have begun at the Omega/Omega EP Laser Facility.

**Shell material**: CD  
**Shell diameter**: \(\sim 870 \, \mu m\)  
**Shell thickness**: \(\sim 40 \, \mu m\)

**Implosion**
- **Energy**: \(\sim 18 \, kJ\) (54 beams)  
- **Wavelength**: 351 nm  
- **Pulse shape**: Low-adiabat, \(\alpha \approx 1.5\)  
- **Pulse duration**: \(\sim 3\) ns  
- **Implosion velocity**: \(\sim 2 \times 10^7\) cm/s

**Target focal spot, log scale**
- \(R_{80} = 21 \, \mu m\)

**Gold cone**
- 10 \(\mu m\), 15 \(\mu m\), 10 \(\mu m\), Center of shell
- 40 \(\mu m\)

**Heating beam**
- **Energy**: \(\sim 1.0 \, kJ\)  
- **Wavelength**: 1053 nm  
- **Pulse duration**: \(\sim 10\) ps  
- **Intensity**: \(\sim 1 \times 10^{19} \, W/cm^2\)

Relative timing varied
A new detector was developed that measures reliably neutron yields in FI-cone experiments

![Image of detector](Image)

- 3-L volume
- Xylene + PPO + bis-MSB + O₂

Liquid scintillators enriched with an O₂ quenching agent have a fast decay time—the γ-ray-induced fluorescence is efficiently suppressed.

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The neutron time-of-flight signals are limited by neutron statistics

- The 2.45 MeV neutron peak is smeared out because of neutron scattering and a large detector volume (~3.5 liter)

- The total neutron yield was obtained by integration
The neutron yield increased more than a factor of two with an appropriately timed OMEGA EP beam.

1.5 ± 0.5 x 10^7 additional neutrons were produced with the short-pulse laser.
Significantly more MeV electrons were produced in the laser forward direction.

Ponderomotive scaling predicts an averaged $T_{\text{hot}} \sim 0.3$ MeV for a Gaussian laser profile (space and time).
2D hydrodynamic simulations predict plasma filling in the cone because of a laser pre-pulse

- The IR critical density contour moved ~100 μm away from the inner cone tip surface
- Self-focusing in pre-plasma and EP-beam non-uniformities might explain the observed hard electron spectrum
- A decrease in coupling efficiency with pre-plasma has been measured in other experiments with cone-wire-targets on EP and TITAN laser

*HYDRA simulations by T. Ma and F. Beg, UCSD
Shock-breakout measurements confirm an intact cone tip up to peak neutron production in integrated experiments.
Hydro-code DRACO\(^1\) and hybrid-PIC code LSP\(^2\) were coupled to simulate integrated fast-ignition experiments\(^3\)

**DRACO:**
- 2-D cylindrically symmetric hydrodynamic code
- Radiation transport is disabled in the present simulations
- Calculates the neutron yield

**LSP:**
- 2-D/3-D implicit hybrid-PIC code
- Hybrid fluid-kinetic description for plasma electrons
- Intra- and inter- species collisions based on modified Spitzer rates
- Lee and More resistivity model for the plasma background
- Thomas-Fermi equation of state

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Low-energy electrons do not heat the core in integrated DRACO-LSP simulation

- Simulation for 10ps, 1kJ, \( R_{80} = 27\mu\text{m} \), 20% EP energy converted into fast electrons. Injection before peak \( \rho R \)
- \( n_{\text{hot}} \) and \( B \) are shown at the peak of the laser pulse
About 3% of the electron-beam energy is deposited in the core region with $\rho>100$ g/cm$^3$

<table>
<thead>
<tr>
<th>Energy deposition</th>
<th>Fraction of e-beam energy</th>
<th>Fraction of laser energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deposition in gold</td>
<td>52%</td>
<td>10%</td>
</tr>
<tr>
<td>Deposition in plastic with $\rho&gt;10$ g/cm$^3$</td>
<td>25%</td>
<td>5%</td>
</tr>
<tr>
<td>Deposition in plastic with $\rho&gt;100$ g/cm$^3$</td>
<td>3%</td>
<td>0.6 %</td>
</tr>
</tbody>
</table>

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<tr>
<th>Neutron yield increase</th>
<th>Neutron yield without hot electrons</th>
<th>6.6×10$^8$</th>
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</thead>
<tbody>
<tr>
<td>Neutron yield with hot electrons</td>
<td>7.4×10$^8$</td>
<td></td>
</tr>
<tr>
<td>Neutron yield increase</td>
<td>8×10$^7$</td>
<td></td>
</tr>
<tr>
<td>Neutron yield increase in the region with $\rho&gt;100$ g/cm$^3$</td>
<td>1.6×10$^7$</td>
<td></td>
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</table>
The hot-electron energy can be too low for a good penetration through the Au cone tip

Mean hot-electron energy assuming ponderomotive scaling
(averaged within FWHM of the spatial and temporal distribution for a Gaussian pulse)

- Mean-free path of 250 keV electrons is a few μm and is smaller than the cone wall thickness
- Higher laser intensities are required
The simulations predict an improved fast electron coupling at higher laser intensity

Simulation for 10ps, 2.6kJ, $R_{80}=15\mu$m. Injection before peak $\rho R$

- CE (>100 g/cm³) improves from 0.6% to 2.4%
- CE (>10 g/cm³) slightly improves from 5% to 6%
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