Status of Integrated Fast- and Shock-Ignition Experiments on OMEGA

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CD shell \( \sim 870-\mu \text{m diam} \)
Driver energy \( \sim 18 \text{ kJ} \)
Short pulse \( \sim 1.3 \text{ kJ} \)
Pulse duration \( \sim 10 \text{ ps} \)
Focus \( \sim 40-\mu \text{m diam} \)

No short pulse

With short pulse

Omega Laser Facility
Users’ Group Workshop
Rochester, NY
29 April – 1 May 2009
Summary

Fast and shock ignition are investigated on the Omega Laser Facility

• Integrated cone-in-shell fast-ignition experiments with up to 1.3 kJ of short-pulse energy and ~18 kJ of long-pulse energy have begun.

• A significant increase in x-ray emission is measured with the higher OMEGA EP laser energy.

• Neutron measurements are challenging due to a strong x-ray background and mitigation techniques are discussed.

• Experiments with shock-ignition pulses show a 4× improvement in yield and 30% more areal density compared to conventional pulses.

• Shock-ignition experiments with 40 beams for fuel assembly and 20 delayed high-intensity beams show significant coupling of shock- and fast-electron energy into the target.

Two-step ignition processes offer the possibility of higher target gain for a fixed laser energy.
Collaborators


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Fast and shock ignition can trigger ignition in massive (slow) targets leading to high gains.

- **Potentially high gains, stable implosions**
  - Gain $G \sim 50$
  - 1-D maximum gain if ignition occurs $\sim \frac{1}{V_i^{1.3}}$
  - Accessible by fast and shock ignition

- **Conventional hot-spot ignition**
  - $V_{\text{min}} \sim 3 \times 10^7$
    - Hot-spot ignition fails
  - $V_{\text{max}} \sim 5 \times 10^7$
    - Quenching by hydro-instabilities

$E_{\text{laser}} = 1 \text{ MJ}$
Integrated fast-ignition experiments with re-entrant cone targets have begun at the Omega/Omega EP Laser Facility.

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**Energy**

$$\sim 18 \text{ kJ (54 beams)}$$

**Wavelength**

$$351 \text{ nm}$$

**Pulse shape**

Low-adiabat, $$\alpha \approx 1.5$$

**Pulse duration**

$$\sim 3 \text{ ns}$$

**Implosion velocity**

$$\sim 2 \times 10^7 \text{ cm/s}$$

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**Shell material**

CD

**Shell diameter**

$$\sim 870 \mu m$$

**Shell thickness**

$$\sim 40 \mu m$$

**Shell fill**

Empty

**Cone material**

Gold

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**Energy**

$$\sim 1.3 \text{ kJ}$$

**Wavelength**

$$1053 \text{ nm}$$

**Pulse duration**

$$\sim 10 \text{ ps}$$

**Intensity**

$$\sim 1 \times 10^{19} \text{ W/cm}^2$$

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**Target focal spot, log scale**

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

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**J. Bromage et al., Opt. Express 21, 16,561 (2008).**
The cone has to withstand the plasma pressure up to peak compression, ensuring a plasma-free path for the short-pulse beam.

- Streaked optical pyrometer (SOP) measures the breakout through 15-μm-thick cone tip.
- Shock breakout at 3.50±0.05 ns is close to peak compression.
- Areal density from 2-D hydrocode simulations.
- Time of \((\rho R)_{\text{max}}\) is close to optimum injection time for fast electrons.
Pointing and timing of the short-pulse beam was achieved with ~20-μm and ~50-ps accuracy.

Drive laser only (18 kJ, spherical shell)

Short pulse only
Black + target chamber center
Red + nominal OMEGA EP pointing

Two orthogonal x-ray pinhole camera views provide the spatial information

- The neutron temporal diagnostic operating in hard x-ray mode provides temporal information
- Measured time of short-pulse interaction: 3.50±0.05 ns
A significant increase in x-ray emission is measured with higher OMEGA EP laser energy.

Time-integrated x-ray pinhole images $E_{ph} = 2$ to 7 keV, $\Delta t = 3.5$ ns
No significant change in x-ray emission was measured for various time delays and 500 J short-pulse energy.

- X-ray pinhole images (1 × 1-mm regions, 2 to 7 keV)
- Shell peak compression and shock breakout inside cone is at ~3.5 ns
Neutron measurements are challenging in fast-ignition integrated experiments because of a strong x-ray background.

Fast electrons streaming through the high-Z cone material produce a significant $\gamma$ pulse that overwhelms the neutron time-of-flight diagnostics for $E > 500$ J.
The neutron detectors are strongly affected by the hard-x-ray background.
Integrated 2-D hydrodynamic DRACO/LSP simulations were performed for various experimental conditions.

- 20° half-divergence angle of electron beam
- Calculations do not account for transport through cone wall
- 15-μm gold wall thickness will have significant effect on energy transport
- The expected n yields below 1 kJ are in the range of the current noise level of 12-m NTOF
A liquid scintillator neutron time-of-flight detector is being developed to suppress the x-ray background induced fluorescence.

Liquid scintillators with a molecular O₂ quenching agent have a fast decay time and are promising detectors to measure the D₂ neutron yield.

Courtesy of Ronald Lauck, PTB (Physikalisch Technische Bundesanstalt, Braunschweig, Germany).
Copper cone targets will be tested in future experiments

- Reduced x-ray bremsstrahlung emission
- Improved fast-electron energy transport through cone wall for lower-Z elements

**Cone type** | **t (μm) wall thickness** | **d (μm) tip diameter** | **Φ (°) full cone angle**
---|---|---|---
I | 20 | 20 | 34
II | 25 | 40 | 40
III | 30 | 60 | 46
A Kirkpatrick–Baez x-ray microscope with a WB$_4$C multilayer mirror will image the Cu K-shell emission.

\(K\alpha\) emission from Cu-doped CH shells will be used to infer fast-electron heating

- ITS Monte Carlo code simulations by A. MacKinnon and D. Hey assuming 1% atomic Cu in 40 \(\mu m\) CH shell

- Predicted good signal level for KB instrument
Shock ignition relies on a shaped laser pulse with a trailing high-intensity spike.

The ignitor shock wave significantly increases its strength as it propagates through the converging shell.
CH shells have been imploded on OMEGA to test the performance of shock-ignition pulse shapes.

\[ E_L = 19 \text{ kJ}, \alpha = 1.3, \quad V_i = 1.7 \times 10^7 \text{ cm/s}, \text{ SSD off} \]

\[ Y_n = 2 \pm 0.2 \times 10^9 \]

\[ Y_n = 8 \pm 0.8 \times 10^9 \]

The neutron yield increases considerably when a shock is launched at the end of the pulse.
The shock-ignition pulse-shape implosions show improved areal densities and neutron yields.

- The measured-to-calculated neutron-yield ratios are close to 10% for a hot-spot convergence ratio of 30.
Laser–plasma interaction during the spike pulse and hot-electron generation are important issues for shock ignition.

Shock-ignition target with 350-kJ total energy

- Laser intensity $I_{\text{Laser}}$
- Density $\rho R$

$\rho R$ range of 100 keV $e^-$

Shock-launching time (ns)

- 1-D 350 kJ
- Marginally igniting (no hot $e^-$)
- Boosted margin (with hot $e^-$)

Hot $e^-$ with Maxwellian $T_{\text{hot}} = 150$ keV, $E_{\text{hot}} = 17\%$ of spike energy, treated using a multigroup diffusion model*

*LILAC simulations by C. D. Zhou and R. Betti
Hot-electron generation and laser–plasma instabilities are studied at ignition-relevant spike intensities

- 60 OMEGA beams are split into 40 low-intensity drive beams and 20 tightly focused, delayed beams (up to $2 \times 10^{16}$ W/cm$^2$)
- Hydrodynamic performance and laser backscattering are studied
- Preliminary results are moderate $T_{\text{hot}} \sim 45$ keV, $\sim 10\%$ conversion efficiency $E_{\text{spike}} \rightarrow E_{\text{hot}}$, $\sim 20\%$ backscattering at $5 \times 10^{15}$ W/cm$^2$ (SRS + SBS)
A significant coupling of high-intensity-pulse energy into the capsule is measured, despite a large target-illumination nonuniformity.

- ~10% power imbalance in current experiment
- Repointing the beams will reduce power imbalance to 2%, similar to spherical 60-beam illumination conditions
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