OMEGA Experiments on the Shock-Ignition ICF Concept

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Summary

The first experimental results of the shock-ignition concept show significant improvement in performance

- Direct-drive shock ignition promises ~3 times lower driver energy for hydro-equivalent high-gain targets than the conventional ICF concept.

- Systematic studies of low-adiabat ($\alpha \approx 1.5$), warm-plastic-shell implosions were performed on OMEGA with short-picket and high-intensity spike pulses.

- The spike shock-generated CH-shell implosion showed a factor of ~4 enhanced fusion-product yields and higher $\langle \rho R \rangle \sim 0.2$ g/cm² indicating a higher compression and better stability.

- Initial shock-ignition experiments with cryogenic D$_2$ and DT targets were performed showing ~1-D–like fuel assembly and up to 12% yield-over-clean.

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

- Potentially high gains, stable implosions
- Conventional hot-spot ignition
- Accessible by fast and shock 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

\[ G (1 \text{ MJ}) > 100 \]  
\[ G (1 \text{ MJ}) \sim 50 \]  
\[ 1 - D \text{ maximum gain if ignition occurs} \sim \frac{1}{V_i^{1.3}} \]
The energy required for isobaric ignition depends on implosion velocity and adiabat.

Isobaric fuel assembly

\[ P = P_{hs} = P_s \]

\[ \alpha = \frac{P_{\text{plasma, shell}}}{P_{\text{Fermi}}} = \text{shell adiabat} \]

\[ V_i = \text{implosion velocity} \]

Laser-energy scaling for direct-drive isobaric ignition

\[ E_{\text{isob-ign* Laser}} \sim \alpha^{1.8} \frac{1}{V_i^6} \]

The ignition condition is more favorable for a non-isobaric fuel assembly with a peaked pressure*.

For adiabatic compression of the hot spot

$$\Phi \approx \left( \frac{P_{hs}}{P_{iso}} \right)^{2.5}$$

$$E_{non-isob-ign} \sim \frac{E_{isob-ign}}{\Phi}$$

A non-isobaric fuel assembly can be produced by shocking the target just before peak compression.

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A shaped laser pulse with high intensity spike launches a strong shock wave for ignition.

![Graph showing laser power and time with a spike]

The ignitor shock wave significantly increases its strength as it propagates through the converging shell.

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L. J. Perkins et al., (JO3.00014)
A. J. Schmitt et al., (PO6.00015)
1-D marginal shock ignition requires thick shells, low adiabats, and ~350 kJ of laser energy*

\[ E_L = 350 \text{ kJ}, \quad V_i = 2.4 \times 10^7 \text{ cm/s}, \quad \alpha = 1, \quad \lambda_L = 0.35 \mu m \]

- Standard pulse shape abs. frac. = 0.55
- Shock-ignition pulse shape abs. frac. = 0.50

\footnote{R. Betti et al., IFSA proceedings (2007).}
Shock-ignition pulse shapes lead to higher compression and more favorable ignition conditions.
A hydrodynamic-equivalent conventional hot-spot isobaric target requires ~1.2 MJ to achieve marginal ignition.
Hot electrons of moderate energies produced during the shock spike can be beneficial to shock ignition.

Shock-ignition target with 350-kJ total energy

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

Three major shock-ignition issues are addressed in OMEGA laser experiments

- It is studied how the impulsive acceleration created by the ignition shock wave affects the fuel assembly.

- Varying the timing of the peaks in the laser pulse shape is used to study the timing of the shock waves and to optimize the implosion.

- Plastic-shell implosions were used to study how fuel–shell mixing affects the yield performance for shock-ignition pulse shapes.

- Only shocks with moderate strength can be launched at the end of the pulse on OMEGA.
CH shells have been imploded on OMEGA to test the performance of shock-ignition pulse shapes.

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

- The neutron yield increases considerably when a shock is launched at the end of the pulse.

Yield

- $Y_n = 2 \pm 0.2 \times 10^9$
- $Y_n = 8 \pm 0.8 \times 10^9$
With the high-intensity spike pulse there is a shock wave driven into the capsule.

1-D LILAC hydrodynamic simulation for shot 46078 (25-atm D₂) shows the formation and evolution of the shock wave launched by the late spike.
No significant effect of SSD smoothing is observed in 40-μm shell, relaxation-picket, low-adiabat implosions.

With a high hot-spot convergence-ratio the fuel–shell mixing strongly quenches the fusion reactions.
The correct timing of the shock waves is crucial for an optimized performance of the implosion.
The implosion was optimized with respect to the timing of the picket pulse with fixed spike timing.

- Measured neutron yield: $\times 10^9$
- Measured proton yield: $\times 10^6$
- Measured $\langle \rho R \rangle$: g/cm$^2$

**Graphs:**
- **Yield vs. Picket delay (ps):**
- **Areal density vs. Picket delay (ps):**

25-atm D$_2$, $E_L \sim 17$ kJ, spike at 2.8 ns
The spike timing has a significant effect on the measured neutron yield.

25-atm D₂, $E_L = 17$ and 19 kJ

Measurement

- 18.6 kJ
- 19.4 kJ

1-D simulation

- 18.6 kJ
- 19.4 kJ

No spike

Power (TW)

Intensity (W/cm² × 10¹⁴)

Time (ns)
The high yield-over-clean at high convergence ratio shows better stability with shock-ignition pulse shape. The measured to calculated neutron-yield ratios are close to 10% for a hot-spot convergence ratio of 30.

**Graph:**
- **X-axis:** Hot-spot convergence ratio
- **Y-axis:** Neutron YOC (%)
- Data points for 'With spike' and 'Without spike' are shown.

**Equation:**
\[ CR = \frac{\text{Inner target radius}}{\text{Minimum hot-spot radius}} \]
Downshifted secondary proton spectra measure* $\langle \rho R \rangle = 0.2$ g/cm$^2$ and $\langle \rho R \rangle_{\text{max}} > 0.3$ g/cm$^2$

Shot 48674, $E_L = 18.0$ kJ, D$_2$ 8.3 atm

D + D $\rightarrow$ $^3$He + n

$^3$He + D $\rightarrow$ p + $^4$He

$\langle \rho R \rangle_{\text{max}} > 0.3$ g/cm$^2$

$\langle \rho R \rangle = 0.2$ g/cm$^2$

Higher $\langle \rho R \rangle$ exceeding $= 0.2$ g/cm$^2$ where measured in implosions with late spike

The shock-ignition pulse-shape implosions show an improved performance with respect to compression and neutron yields.
The fuel assembly is close to the one-dimensional predictions with the code LILAC.

All shock-ignition pulse shapes

Experimental $\langle \rho R \rangle$ (g/cm²)

Calculated $\langle \rho R \rangle_n$ (g/cm²)

Neutron rate (1/s) ($\times 10^{20}$)

$\rho R$ (g/cm²)

Time (ns)

Shot 48674, D$_2$ 8 atm, CR = 22, $E_L = 17.9$ kJ, no SSD

YOC $\approx$ 10%

Initial experiments of the shock-ignition concept were performed with cryogenic D\textsubscript{2} and DT targets.

- The D\textsubscript{2} implosion measured $\langle \rho R \rangle = 0.18 \pm 0.05$ g/cm\textsuperscript{2} achieving 90% of the 1-D prediction (0.20 g/cm\textsuperscript{2}).
- The neutron YOC’s were 5% and 12% for the D\textsubscript{2} and DT implosions.
- The simulations show that no shock was produced by the spike pulse.

The first few shock-ignition cryo-implosions on OMEGA were among the best performing (in terms of YOC and $\rho R$) but did not yet exceed the performance of standard pulse shapes.
- Pulse shape with SSD is not optimal (spike rise time).
- More cryo shots are coming up in the future.
The first experimental results of the shock-ignition concept show significant improvement in performance:

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The spike pulse provides a higher compression

Measurement

1-D simulation

25-atm D₂, $E_L = 17$ and 19 kJ