Monochromatic Backlighting of Direct-Drive Cryogenic DT Implosions on OMEGA

Top view not to scale

Bragg angle ($\theta_B$)

High-intensity laser pulse

Target

Backlighter

Shaped crystal

Rowland circle

Core

Shell

Backlighter

Detector

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58th Annual Meeting of the American Physical Society
Division of Plasma Physics
San Jose, CA
31 October–4 November 2016
Summary

The effects of perturbations on direct-drive DT cryogenic implosions are diagnosed with monochromatic x-ray backlighting

- A crystal imager* is used for short pulse (20 ps), monochromatic x-ray backlighting** (1.865 keV) of 60-beam OMEGA DT cryogenic implosions

- Low-mode nonuniformities have been studied† close to stagnation in experiments with pre-imposed shell-thickness variations

- The effects of localized perturbations like the target stalk have been observed with both mass-equivalent CH and DT cryogenic targets

- The level of mixing of plastic ablator with the DT ice has been inferred at in-flight aspect ratios (IFAR’s) ~ 20 and adiabats from 2.5 to 4.0

All three sources of perturbations contribute to the performance degradation observed in the experiments.

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**R. Epstein et al., TO5.00005, this conference.
†I. V. Igumenshchev, CI3.00002, this conference (invited).
Collaborators


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Outline

• Motivation
  • Experimental setup
  • Low modes
  • Imprint and mix
  • Localized perturbations
The expected target performance is determined by the laser pulse shape and the target dimensions.

Adiabat and IFAR are controlled by pulse shaping.

\[ E_L = 18 \text{ to } 25 \text{ kJ} \]
\[ v_{\text{imp}} = 2.4 \text{ to } 3.7 \times 10^7 \text{ m/s} \]
\[ \alpha = 1.9 \text{ to } 4.3 \]
\[ \text{IFAR} = 10 \text{ to } 20 \]

- Adiabat \( \alpha = P/P_{\text{Fermi}} \)
- \( v_{\text{imp}} \) = Implosion velocity
- \( E_L \) = Laser energy
- \( \text{IFAR} = \text{shell radius/shell thickness} \)
Simulations indicate that both short- and long-wavelength perturbations limit the target performance

Generalized Lawson criterion

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

Image from NNSA framework document

* R. Betti et al., Phys. Rev. Lett. 114, 255003 (2015);
The x-ray or neutron images of the hot spot do not reflect the shape of the dense shell.

The goal of monochromatic backlighting is to radiograph the compressed shell close to peak compression.

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The goal of monochromatic backlighting is to radiograph the compressed shell close to peak compression.

Peak neutron production $t = 2.57$ ns

Sources
- 20-μm offset
- Beam overlap
- 10% imbalance
- 10-μm-rms mispointing
- 5-ps-rms mistiming

**ASTER** 3-D simulations

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The nonuniformities in the target evolve significantly in the 100 ps before peak neutron production.
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Monochromatic backlit images of DT cryo implosions are recorded with a shaped Bragg crystal-imaging system

- The backlighter foil is not in the focus of the imaging system, so the backlighter uniformity does not depend on the laser-intensity distribution
- A collimator blocks the line of sight (LOS) to the backlighter, minimizing the background from the short-pulse laser
- A direct LOS block shields the detector from background produced by the implosion target
Better spatial resolution and a higher brightness of the backlighter will improve the performance of the radiography setup*

- 25 kJ low-adiabat pulses
- 20-ps exposure, 20-ps backlighter
- ~200-eV blackbody equivalent backlighter brightness

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$LILAC/Spect3D$ profile and image at $CR = 13$

- Perfect spatial resolution
- 15-μm spatial resolution

*R. Epstein et al., TO5.00005, this conference.
Three key innovations were required to make it possible to field a crystal-imaging system on cryogenic shots

- An aspherically shaped substrate was designed* to reduce the optical aberration of the imager at the relative large angle of incidence of 6.2°

- A fast target-insertion system* positions the backlighter target within ~100 ms after the cryo shroud has been removed

- An ultrastable optoelectronic trigger system with a jitter of ~1.5-ps rms triggers the 40-ps exposure time framing-camera detector


**HTS: hardware timing system
High-quality backlit images of the compressed DT shell were taken at CR ~7

The intensity profile of the backlighter must be removed to infer the absorption of the shell.*

*XRFC: x-ray framing camera
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The influence of low-mode nonuniformities was studied using targets with shell-thickness variations.

- Shell-thickness nonuniformity
  ~0.1-\(\mu\)m rms
- Ice-thickness nonuniformity
  <1-\(\mu\)m rms

- Shell-thickness nonuniformity
  2- to 4-\(\mu\)m peak to peak
- Ice-thickness nonuniformity
  ~2-\(\mu\)m rms

Fiducial glue spot
~30 \(\mu\)m diam

Not to scale
Low-mode structure is seen in the radiograph at a CR of 7 for a uniform shell-thickness target.

- Exposure time of 40 ps, ~100 ps before bang
- DT(60 μm) CH(12 μm), 888-μm diam, offset < 10 μm
- $\alpha = 2.5$, IFAR ~10, YOC = 20%, $\rho R/clean = 78\%$

YOC: yield over clean
Both radius and magnitude of peak absorption show a variation as a function of azimuthal angle comparable to the simulations.

- An $\ell = 1$ of $\sim 5 \mu m$ can be introduced by the choice of image center
- $\ell = 1$ with an amplitude of $\sim 10 \mu m$ on the radius of peak absorption
- All low-mode effects accounted for in the simulation; no stalk
The influence of low-mode nonuniformities was studied using targets with shell-thickness variations

- Shell-thickness nonuniformity: \(\sim 0.1\mu m\) rms
- Ice-thickness nonuniformity: <1\(\mu m\) rms

Fiducial glue spot: \(\sim 30\mu m\) diam

- Shell-thickness nonuniformity: 2- to 4\(\mu m\) peak to peak
- Ice-thickness nonuniformity: \(\sim 2\mu m\) rms
The radiograph from a shell with 4-μm wall thickness variation shows a low-mode structure for a CR \(\sim 10\)

- Exposure time of 40 ps, horizontal 4 μm Δ, \(\sim 50\) ps before bang
- DT(60 μm) CH(11 μm) 960-μm diam, offset < 10 μm
- \(\alpha \sim 2\), IFAR \(\sim 15\); YOC = 8%, \(\rho R\)/clean = 41%
Both radius and magnitude of peak absorption show a variation as a function of the azimuthal angle

- An $\ell = 1$ of $\sim 5 \mu m$ can be introduced by the choice of image center
- $\ell = 1$ with an amplitude of $\sim 10 \mu m$ on the peak absorption
- $\ell = 2$ with an amplitude of $\sim 7 \mu m$ on the hot spot
Post-processed DRACO* 2-D simulations** show similar features as the experimental data.

**R. Epstein et al., TOS.00005, this conference.
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Core x-ray emission indicates that carbon from the ablator mixes into the core at peak compression*

- Radiography was used to study early-time mix with $\alpha = 2.5$ to 4 and IFAR = 17 to 20 at convergence ratios of 4 to 7
- Some shots had Germanium doped in the shell**

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**S. P. Regan et al., TOS.00004, this conference.
Simulations assuming the mixing of carbon into the DT shell can reproduce the measured absorption.

- Exposure time of 200 ps, CR = 4
- DT(60 $\mu$m) CH(8 $\mu$m), 860-$\mu$m diam, offset ~25 $\mu$m
- $\alpha \sim 2.5$, IFAR ~ 17; YOC = 7%, $\rho R$/clean = 78%

The depth of the mixing can be inferred by separating the DT ice into layers in the LILAC simulations.
A trend for mixing caused by imprint as a function of adiabat can be inferred from the experimental data.
Post-processed highly resolved DRACO simulations show behavior similar to the experiment

- Simulations include perturbations up to modes of $\ell = 300$
- Low-mode perturbations are included: pointing, timing, energy
- DT$(45 \, \mu m)$ CH$(11 \, \mu m)$, 860-$\mu m$ diam
- $\alpha \sim 2.5$, IFAR $> 25$
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A 20-μm amplitude stalk feature is seen in backlit images of a mass-equivalent CH target at a CR = 2.5

- The radius of the 50% rise on the absorption feature is evaluated by taking lineouts from the center of the image
A 10-\(\mu\)m amplitude stalk feature is visible in one low-adiabat (~2.5) cryogenic DT implosion at a CR of 7

- The radius of peak absorption is evaluated by taking lineouts from the center of the image
- The \(\ell = 1\) order distortion has been removed
A comparable stalk effect is also visible in 2-D DRACO simulations of a similar target configuration.

- **DRACO** simulations are post-processed using **Spect3D**
- The radius of peak absorption is evaluated by taking lineouts from the center of the image.
Open questions

Quantifying the impact of laser and target imperfections on the implosion performance is an active area of research

- Radiography can be used to study several different effects
  - target placement can be evaluated using pre-imposed target offsets
  - changing the size of the glue spot will help to quantify stalk effects
  - smoothing by spectral dispersion (SSD) on/off experiments will examine laser imprint

- The performance of the shaped crystal imaging system will be improved
  - higher-quality quartz crystals will be used to increase the resolution of the shaped crystal imager; ray tracing shows resolutions < 1 μm
  - prepulses and foam targets will be tested to increase the brightness of the Si backlighter
Summary/Conclusions

The effects of perturbations on direct-drive DT cryogenic implosions are diagnosed with monochromatic x-ray backlighting

- A crystal imager* is used for short pulse (20 ps), monochromatic x-ray backlighting** (1.865 keV) of 60-beam OMEGA DT cryogenic implosions
- Low-mode nonuniformities have been studied† close to stagnation in experiments with pre-imposed shell-thickness variations
- The effects of localized perturbations like the target stalk have been observed with both mass-equivalent CH and DT cryogenic targets
- The level of mixing of plastic ablator with the DT ice has been inferred at in-flight aspect ratios (IFAR’s) ~ 20 and adiabats from 2.5 to 4.0

All three sources of perturbations contribute to the performance degradation observed in the experiments.

**R. Epstein et al., TO5.00005, this conference.
†I. V. Igumenshchev, CI3.00002, this conference (invited).
Experimental target performance is a strong function of adiabat and IFAR

- The ratio of the measured areal density $\rho R$ and average hot-spot pressure $\langle P_{hs}\rangle$ over the 1-D simulated values are used as a metric for the performance of the implosion.

- The hot-spot pressure can be inferred from the observable quantities: neutron yield, ion temperature, and neutron rate.

The lineouts of the backlit images from the crystal imager must be corrected for the backlighter shape.

- The backlighter is assumed to be uniform.
- It is convolved with a Gaussian representing the geometric resolution of the imager.
- The width and amplitude of the backlighter is adjusted to match the signal.
ASTER 3-D simulations* show similar low-mode features as the experimental data

Both radius and magnitude of peak absorption show a small variation as a function of azimuthal angle.

- An $\ell = 1$ of $\sim 5 \, \mu m$ can be introduced by the choice of image center.
- $\ell = 1$ with an amplitude of $\sim 10 \, \mu m$ on the radius of peak absorption.
Spect3D simulations with 0.2% mix of the 0.7% Ge-doped CD shell match the measured absorption

- According to simulations, the mass of the DT shell is \( \sim 20 \, \mu g \)
- The mass of the CH(0.7%) in the shell is \( \sim 120 \, \text{ng} \)
- According to LILAC, the hot spot is \( \sim 10\% \) of the total mass, therefore assuming only \( \sim 50\% \) of the mix gets into the hot spot at \( \sim 6 \, \text{ng} \)
The emission spectrum from Spect3D with 0.1% mix into the core compares favorably with measured spectrum from the x-ray specrometer (XRS).

- XRS is an absolutely calibrated time-integrated x-ray spectrometer
- The emission time is assumed to be 100 ps
- The Spect3D spectrum is broadened to account for the instrument resolution
- The experimental spectrum is shifted to match the Spect3D continuum
A number of operational issues prevent the crystal imager from achieving its potential performance

- With an \( \sim 15-\mu m \) edge response the imager does not achieve its predicted resolution of \(<5 \, \mu m\), most likely caused by crystal imperfections.
- Pointing variations in the crystal-insertion mechanism lead to clipping on the x-ray framing-camera strip.
- Variations in the OMEGA EP beam focus location prevent good centering of the imploded core with respect to the backlighter.
Several improvements to the setup of the crystal-imaging system are in progress

- The cause of this drift in the OMEGA EP beam focus location is being investigated and will be addressed.
- A new pointing scheme will be implemented to eliminate the pointing variations in the crystal-insertion mechanism.
- A higher-quality quartz substrate will be used in the future to improve the spatial resolution from \( \sim 15 \, \mu m \) to \( < 5 \, \mu m \).
- An experimental program to increase the brightness of the Si backlighter has started.