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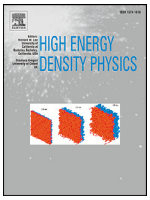

# Simulation and analysis of time-gated monochromatic radiographs of cryogenic implosions on OMEGA

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ABSTRACT

Spherical polymer shells containing cryogenic DT ice layers have been imploded on the OMEGA Laser System and radiographed using Si backlighter targets ($h\nu = 1.865$ keV) driven with 20-ps IR pulses from the OMEGA EP Laser System. We report on a series of implosions in which the deuterium–tritium (DT) shell is imaged for a range of convergence ratios and in-flight aspect ratios. The shadows of the converging DT ice and polymer shells are recorded while the self-emission is minimized using a time-resolved (40-ps) monochromatic crystal imaging system. The images acquired have been analyzed for the level of ablator mixing into the DT fuel (even 0.1% of carbon mix can be reliably inferred). Simulations are compared with measured x-ray radiographs to provide insight into the early time and stagnation stages of an implosion, to guide the modeling efforts to improve the target designs, and to guide the development of this and other imagining techniques, such as Compton radiography.

## 1. Introduction

Layered cryogenic DT targets are the baseline approach to achieving ignition in direct-drive [1] inertial confinement fusion (ICF) [2] experiments [3]. Steady progress has been made in experiments with hydrodynamically equivalent [4], energy-scaled implosions [5–10] on the OMEGA Laser System [11]. Recent implosion experiments on OMEGA have reached a record core pressure of 56 ± 7 GB for direct-drive ICF cryogenic DT implosions [10]. This quality of performance, hydrodynamically scaled to the energy of the National Ignition Facility (NIF) [12], is equivalent to ~60% of the value of the Lawson parameter required for thermonuclear ignition [13,14] and similar to indirect-drive [15] implosion performance [16,17]. This measured core pressure is ~40% lower than simulated spherically symmetric 1-D performance. Monochromatic soft x-ray radiography [18] is being developed to complement implosion performance measurements from other diagnostics, such as areal-density measurements by charged-particle spectroscopy [8,19]; to view directly the overall shell integrity and divergence from spherical symmetry, resulting from the low-order hydrodynamic effects of drive nonuniformity, target-positioning offset, and ice-layer nonuniformity; and to provide a new and direct measure of the possible contamination of the DT fuel by ablator material.

Radiography in its many forms has been a standard tool throughout the history of ICF [1,15]. Implosion radiography on OMEGA has progressed from room-temperature targets [20], to the first radiography of cryogenic targets [21,22], and to the first attempts at Compton radiography [23]. More recently, x-ray radiography has been used with gas-filled room-temperature targets to measure nonspherical shell distortions of targets imploded with polar direct drive [20,24] and to measure the implosion velocity and mass ablation rate of capsules imploded on the NIF with indirect drive [25].

From very early on, monochromatic soft x-ray radiography of the imploding cryogenic DT “payload,” driven by the ablation of an outer CH layer, was a high-priority goal, motivated in part by the fact that the theory of free–free (FF) absorption [26], the dominant soft x-ray absorption process of fully ionized isotopes of hydrogen (H, D, or T), is based on well-known and relatively simple atomic physics that would allow a direct interpretation of the measured radiographic data in terms of the hydrogen mass distribution. More recently, radiographic absorption by the unablated trace of the CH polymer shell has provided additional information about shell dynamics and the amount of ablator CH mixed into the DT fuel [18].

Monochromatic soft x-ray radiographs of cryogenic (cryo) deuterium–tritium (DT)-filled polymer shells imploded on the OMEGA

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Laser System [11] have been obtained with silicon K-shell emission-line backlighters driven by the OMEGA EP short-pulse laser [27]. These images have been examined at times of moderate convergence (at convergence ratios [4] near $\mathrm{CR} \approx 10$, where $\mathrm{CR} \equiv R_{\mathrm{initial}}/R$, with $R$ being the peak-density radius of the imploding shell) for consistency with predicted implosion performance and for evidence of fuel–shell mix driven by hydrodynamic instabilities. The consequences of scaling this technique to higher convergence will be discussed, considering the limitations of this technique imposed by self-emission from the hot cores of these implosions and the detectability of the radiographic absorption.

Self-emission background from the stagnating core is the primary limitation of soft x-ray radiography of the stagnating DT shells. Core emission and the shell shadow are distinct features on radiographs, but finite spatial resolution spreads the self-emission over the radiographic shadow. The core self-emission spectrum drops with increasing spectral energy, but the opacity of the stagnating DT shell, which must be large enough to cast a measurable shadow, also drops with increasing backlight energy. Following the implosion closer to the time of peak compression, compression and convergence raise the optical thickness of the shell very rapidly, requiring higher backlight energies to keep the shell's optical thickness within a measurable range of radiographic transmission, roughly midway between completely transparent and completely opaque, but the core self-emission also rises rapidly as the core compresses. In the hard-backlighter limit, where the self-emission spectrum has fallen off completely, Compton radiography may provide an alternative to soft x-ray radiography at stagnation [23].

The experimental setup will be described here only briefly since it has been described elsewhere [18,28], and the theory of the formation of soft x-ray radiographs will be reviewed to illustrate the challenges and limitations of the method.

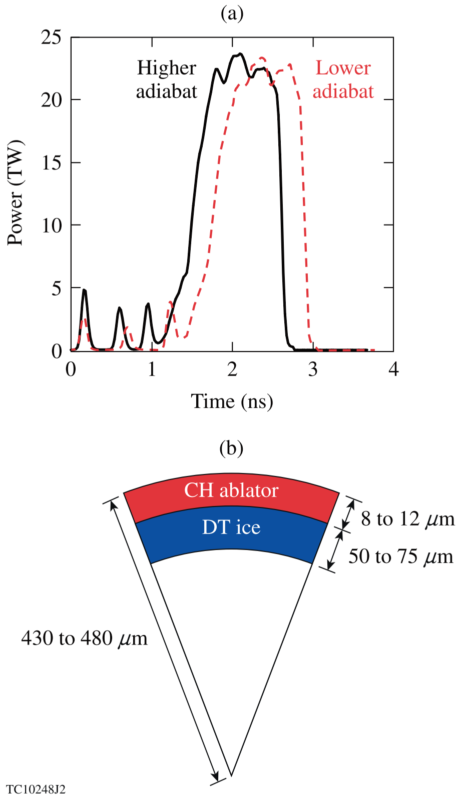

**Fig. 1.** Representative target and laser pulses: (a) The laser drive pulse consists of a series of three picket pulses to set the shell adiabat and control shock coalescence and a high-intensity main drive pulse with total energy of 22–25 kJ. The examples "higher adiabat" (solid curve) and "lower adiabat" (dashed curve) are typical. (b) The cryogenic DT capsules consist of a thin, 8- to 12-μm CH, CD, or doped-CD ablator coated on the inside with a 50- to 75-μm-thick DT cryogenic ice layer.

## 2. Experimental setup

The laser pulse shape, illustrated by two typical "three-picket" examples in Fig. 1(a), drives the implosion of CH polymer shells of various thicknesses containing a cryogenic DT fuel layer, illustrated by a typical example in Fig. 1(b). The laser pulses in Fig. 1(a) begin with three spikes or "pickets" that launch a sequence of three shocks through the target layers as the ablation pressure sets the shell into motion. The strength and timing of these shock waves determine the adiabat parameter $\alpha$ of the imploding shell [4], which is defined as the imploding-shell mass average of the ratio of the pressure to the zero-temperature or "Fermi" pressure $P_{\mathrm{Fermi}}$, $\alpha \equiv P/P_{\mathrm{Fermi}}$, when the imploding shell has reached a radius $R$ equal to 2/3 of its initial radius. This, along with the shell's in-flight aspect ratio (IFAR), determines the hydrodynamic stability characteristics of the shell and its resistance to breakup near stagnation. The IFAR is defined at the same time as $\alpha$ as $\mathrm{IFAR}=R/\Delta R$ [4], where the shell thickness $\Delta R$ is defined as the distance between the two points on its mass-density profile on either side of the peak-density point that are at $1/e$ of the peak density. Low adiabats and high IFAR are both associated with shell instability and reduced implosion performance. In a large ensemble of experimental measurements of peak shell areal densities of implosions covering a range of roughly $2<\alpha<5$ and $13<\mathrm{IFAR}<30$, the "stability boundary" separating implosions that do or do not exceed 85% of their 1-D–predicted areal density is [4]

$$\mathrm{IFAR}_{\mathrm{boundary}} \simeq 20(\alpha/3)^{1.1}. \qquad (1)$$

The monochromatic backlighting setup is illustrated schematically in Fig. 2. The OMEGA EP [27] 1.5-KJ, 20-ps beam drives a Si/He$_\alpha$-emitting backlighter within the OMEGA target chamber. A curved quartz-crystal imager uses Bragg reflection of the Si/He$_\alpha$ emission to provide high spatial resolution and narrow spectral bandwidth to limit the broadband self-emission background from the imploding target [28]. The image is recorded within an x-ray framing camera (XRFC) [29,30]. The backlighter foil is not in the focus of the imaging system, so the backlighter uniformity is weakly dependent on the laser-intensity distribution on the backlighter target. The Bragg crystal is located 0.267 m from the target while the image-plate detector is placed 3.6 m from the crystal for a magnification of ∼15.

Experiments with resolution grids show an ∼15-μm, 10%–90% edge response for the crystal imaging system [18]. Experiments using only the backlighter foil showed that the XRFC system has a jitter of <10-ps rms (root mean square) with respect to the arrival of the OMEGA EP laser on the backlighter target. The timing of the OMEGA EP pulse to the OMEGA laser was measured to ∼10-ps rms using a neutron temporal diagnostic (NTD) [31].

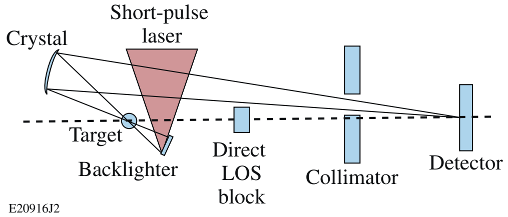

**Fig. 2.** Schematic of the backlighting setup of the spherical crystal imager from [25] (not to scale): The short-pulse laser illuminates a backlighter foil behind the primary target, which is heated by 60 beams from the OMEGA laser (not shown). A direct line-of-sight (LOS) block and a collimator protect the detector [an x-ray framing camera (XRFC)] from background x rays emitted by the backlighter and primary targets. The focusing crystal is suspended 0.267 m from the target, opposite the LOS blockers. The XRFC is mounted 3.6 m from the crystal, achieving a magnification of ∼15.