**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 imaging techniques, such as Compton radiography.

Keywords: Radiography; Inertial Confinement Fusion; Implosion

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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 $\sim 60\%$ 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 $\sim 40\%$ 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 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 $CR \approx 10$, where $CR \equiv R_{\text{initial}}/R$, 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.

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 α 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_{Fermi} , $\alpha \equiv P/P_{\text{Fermi}}$, 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 α as $\text{IFAR} = R/\Delta R$ [4], where the shell thickness ΔR 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 $13 < \text{IFAR} < 30$, the “stability boundary” separating implosions that do or do not exceed 85% of their 1-D–predicted areal density is [4]

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

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 $\sim 15\text{-}\mu\text{m}$, 10% to 90% edge response for the crystal imaging system [18]. Experiments using only the backlighter foil showed that the XRFC system has a jitter of $< 10\text{-ps}$ 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 $\sim 10\text{-ps}$ rms using a neutron temporal diagnostic (NTD) [31].

3. Cryogenic implosion radiography

Radiography of a converged cryogenic target is illustrated in Fig. 3 by a 1-D simulation of a typical target. The radiograph of the spherically symmetric imploded target at a time corresponding to $CR = 11$ consists of two shadows that are the radiographic projections of two thin absorbing layers within the imploded shell. Formally, the unmagnified radiographic projection $I(x)$ of a spherically symmetric object is

$$I(x) = I_0 e^{-\tau(x)}, \quad (2)$$

where x is the radial coordinate in the image plane and I_0 is the imaged intensity of a uniform backlighter in the absence of the object. The optical thickness $\tau(x)$ of the object is the Abel transform [32] of the opacity profile of the object, $\kappa(r)$:

$$\tau(x) = \int \kappa[r(s)] ds, \quad (3)$$

where each point on the backlighter ray path s is identified with its distance r from the center of the object. Each individual ray path is identified by the radial coordinate x , where it intersects the image plane. Figure 3(a) shows the radial temperature (dashed curve) and density (solid curve) profiles, indicating the DT/CH layer boundary, produced by the 1-D radiation–hydrodynamic code *LILAC* [33]. *LILAC* includes full 3-D laser ray trace of the laser light [34], collisional absorption via inverse bremsstrahlung [35], cross-beam energy transfer (CBET) [36], multigroup

diffusive radiation transport with Astrophysical Opacity tables [37], and a nonlocal thermal transport model [7]. The solid curve in the plot in Fig. 3(b) is the radial trace of the “total” or “apparent” radiograph, based on this *LILAC* result, simulated with the atomic-physics radiation-transport postprocessor *Spect3D* [38]. The imaged intensity is plotted in units of the backlighter intensity. The backlighter intensity in this and other simulations in this paper has been set to match the measured ratio of the backlighter intensity to the intensity of the core’s self-emission. The first significant absorbing layer is the shocked DT ice shell near $r \approx 40 \mu\text{m}$, which is the object of interest from the point of view of the implosion performance; the second is the unablated trace of CH near $r \approx 90 \mu\text{m}$ that is left unablated from this relatively thick initial CH layer, providing further indications of implosion dynamics and mix.

The trace of CH at the inner edge of the CH layer is an insignificant feature on the mass-density profile, nearly two orders of magnitude down from the density peak, but it casts a shadow as strong as that of the entire DT shell. This is expected since it is well known that the C outshines and out-absorbs D, T, and H by orders of magnitude under most conditions. Their relative importance in forming radiographs is easily understood by considering the ratio of the respective dominant absorption cross sections,

$$\frac{\sigma_{\text{C}}^{\text{BF}}}{\sigma_{\text{H}}^{\text{FF}}} \propto \frac{1}{a_0^3 n_e} \frac{Z_{\text{C}}^4}{Z_{\text{H}}^2} \left(\frac{kT}{\chi_{\text{H}}} \right)^{1/2} \frac{g_{\text{BF}}}{g_{\text{FF}}} \quad (4)$$

for bound–free (BF) absorption, which is the dominant process for C, and free–free (FF) absorption, which is the dominant process for the isotopes of hydrogen (H, D, or T) [26]. This ratio—a very large number—is written in terms of $a_0^3 n_e$, the number of free electrons per cubic

Bohr radius a_0 ; the respective H and C nuclear charges, Z_H and Z_C ; the hydrogen ground-state ionization energy χ_H , and the temperature T . The Gaunt factors g_{FF} and g_{FF} are shown for completeness [39]. Usually, they vary slowly with temperature and density, so, for the purpose of describing the approximate behavior of these cross sections, we adopt the very common approximation of treating them as constants [40]. In the *Spect3D* simulations reported here, however, accurate opacity values based on the *PrismSPECT* atomic model are used. The ratio of the charge-dependent factors alone,

$$\frac{Z_C^4}{Z_H^2} \approx 1300, \quad (5)$$

contributes three orders of magnitude to this ratio. The radiograph shown here has been simulated assuming perfect spatial resolution. The large opacity of C makes it attractive as a radiographic tracer in material that would otherwise be invisible.

The solid curve in Fig. 3(b) is the total measured radiograph, consisting of a flat backlighter profile with the radiographic absorption cut out of it, which we choose to call the “intrinsic” or “actual” radiograph (dashed curve) plus the self-emission from the implosion (dotted–dashed curve). At the 1865-eV backlighter energy selected by the Bragg reflector, the self-emission is radiated entirely from within the low-density DT core inside the shocked DT shell. With perfect spatial resolution, the core self-emission contributes nothing to the DT shell absorption feature in the radiograph, outside the inner radius of the DT shell. Assuming that the object is spherically symmetric so that Eqs. (2) and (3) apply, the spherical opacity distribution $\kappa(r)$ can be obtained from its radiographic projection by Abel inversion [32]

$$\kappa(r) = -\frac{1}{\pi} \int_r^\infty \frac{d\tau(x)}{dx} \frac{dx}{\sqrt{x^2 - r^2}}. \quad (6)$$

This shows explicitly that the opacity profile at any radius r is obtained only from radiographic measurements exterior to r . Therefore, with perfectly resolved $\tau(x)$ data, the radiographic absorption signal inside the radius corresponding to the radius of the core, where it is obscured by self-emission, is not needed to obtain the DT shell's opacity profile $\kappa(r)$, which requires radiographic data only from outside the core radius. With finite spatial resolution, however, the core self-emission signal bleeds into the DT shell's shadow on the radiograph, obscuring part of the DT-ice shell from view.

Figure 4(a) shows the simulated history of shot 81590 for the nanosecond interval during which the imploding shell approaches and passes through stagnation. The shaded band shows the imploding shell trajectory with a central curve marking the radius of maximum mass density and the boundaries marking the $1/e$ point on either side of the mass-density distribution. Using the shell convergence ratio as a known monotonically increasing function of time, the time axis is also a convergence ratio axis when read with the light labels below the time labels. The end of the laser pulse is seen, ending at about 3.2 ns. The shell areal density is plotted as the dotted-dashed line. The monochromatic spectral self-emission at 1865 eV is plotted in arbitrary units as the dot-dot-dashed curve. This is seen to follow the areal density quite closely, with a doubling time as short as about 20 ps as stagnation is approached. This self-emission competes with the backlighter in forming the radiographic shadow of the imploding DT shell, limiting how close to stagnation the implosion can be followed with soft x-ray radiography. Earlier in time, there is

self-emission from the unablated CH when it is heated by the laser, which stops at the end of the laser pulse. A sequence of simulated radiographs for this simulated implosion is plotted in Fig. 4(b). The selected times indicated in the legend correspond to line-format-coded arrows in Fig. 4(a). The CH and DT shell shadows are clearly seen, except for the radiograph at 3.35 ns, while the unablated CH is still emitting. These radiograph traces have been simulated with an assumed temporal resolution of 20 ps, corresponding to the backlighter pulse width, and a spatial resolution of 15 μm , as described in Sec. 2.

Here, we see that the CH and DT features grow as they converge, except that the DT shadow weakens slightly and does not converge from 3.65 to 3.70 ns, even though the DT shell continues to converge during this time in Fig. 4(a). During this time, the shadow of the unablated CH remnant continues to converge and strengthen. We shall see that the actual underlying absorption component of the total DT-shell radiographic signal does, in fact, converge and strengthen, but the growing self-emission of the core spreads into the DT shell's absorption signal, creating the appearance of a weakening shadow. By this time, the total radiographic signal can no longer be interpreted as the pure absorption signal of the DT shell.

Looking more closely at how self-emission affects a radiograph and how far along an implosion can be followed with radiography, we show two simulated radiographs, 40 ps apart, at $\text{CR} \approx 10$ in Fig. 5(a) and $\text{CR} \approx 16$ in Fig. 5(b). During this time, the total intensity on the radiograph in the core grows to exceed the backlighter intensity. The effect of self-emission on the interpretation of the radiograph is apparent in Fig. 5(b). These plots show radial traces of the total radiograph (solid curve) and two more curves showing the intrinsic radiograph (dashed curve) and the self-emission contribution (dotted-dashed curve) separately. In all these plots, the self-emission is too low to affect the CH shell's absorption feature near $r \approx 100 \mu\text{m}$. This far

from the emitting core, the intrinsic and apparent radiographs are practically identical. At $CR \approx 10$, the DT-ice shell's shadow has just begun to form. Here, the self-emission is relatively low, so the absorption profile at radii above that of peak absorption, which would be Abel inverted to obtain the radial distribution of shell opacity, is still substantially unaffected. The arrows show the radii of peak absorption of the intrinsic and apparent radiographs, below and above the curves, respectively.

At $CR \approx 10$, self-emission does not significantly shift the apparent radius inferred from the apparent radiograph away from the actual radius of the imploding shell at the peak absorption of the intrinsic radiograph. Only 40 ps later, at $CR \approx 16$, the self-emission has become comparable to the backlighter intensity and has lifted the apparent radiograph profile near the core so that the apparent DT shell radius is visibly greater than the actual radius. Figure 5(c) shows the radiograph and its components at $CR \approx 16$ with the spatial resolution improved to $8 \mu\text{m}$ so that less self-emission spreads beyond the actual radius of the emitting core. The result is that the apparent radiograph is closer to the intrinsic radiograph, and the actual and apparent DT-shell radii are much closer. Work is now in progress to develop a shaped crystal imager with an improved spatial resolution of $<10 \mu\text{m}$ [18], as well as brighter backlighters that will allow us to extend soft x-ray radiography to higher convergence.

4. Radiographic measurements

Monochromatic soft x-ray radiographs of cryogenic implosions at modest convergence ($CR \approx 10$) have been obtained on OMEGA. These include measurements of implosions of asymmetric targets or targets imploded with nonuniform drive [18]. The radiograph from OMEGA shot 81590 is shown in Fig. 6(a). The imploding shell forms an annular shadow

roughly $200\text{ }\mu\text{m}$ in diameter centered on a larger elliptical backlighter. Shot 81590 was radiographed at 3.35 ns, at $37\text{-}\mu\text{m}$ core radius, corresponding to $\text{CR} \approx 7$. The calculated areal density ρR at this time was 90 mg/cm^2 . The imaged elliptical intensity profile of the backlighter is the convolution of the backlighter illumination spot and the transfer function of the imager for objects at the backlighter target plane. This backlighter shape is removed or “flattened” for plotting or analysis [28]. Figure 6(b) shows the lineout of the measured backlighter shape—corrected radiograph (solid curve), taken along the dashed line indicated in Fig. 6(a). The lineout is averaged over a sampling width corresponding to the spatial resolution of the image. The lineout of the *LILAC/Spect3D* simulated radiograph (dashed curve) is superimposed on the lineout of the measured image. The backlighter intensity in the simulation was adjusted to reproduce the measured ratio of core self-emission to backlighter intensity at the time of this radiograph.

This radiograph represents a time before the self-emission has exceeded the backlighter intensity. The overall size and shape of the measured radiograph match its 1-D simulation. The outer edge of the simulated radiographic signal is a strongly limb-darkened shadow of a CH shell remnant. The measured radiographic shadow is also limb darkened at the same radius, indicating that the imploded CH shell is essentially intact at this point. The simulated core emission profile is roughly of the same size and shape as the measured core, but the distinct absorption peak associated with the simulated DT shell has been blurred away in the measured radiograph. Finite spatial resolution and motion blurring over the 20-ps duration of the backlighter have been taken into account in the simulation. Nevertheless, the sides of the measured shell shadow slope over a larger scale length than in the simulated image. The implosion is likely to have been affected by hydrodynamic instability that caused perturbations to grow. These include the small degree of

nonuniformity of the illumination distribution of the 60-beam OMEGA Laser System stemming from its intrinsic multibeam geometry [41], beam imbalance, [41,42] target position [6,41], target asymmetry and defects [6,43–45], and the finer-scale speckle illumination nonuniformity existing within each individual beam’s intensity distribution [46]. The hydrodynamic instability of this target shell at the various stages in its implosion can cause these perturbations to grow, although its moderate adiabat $\alpha = 2.5$ and in-flight aspect ratio IFAR ≈ 10 suggest that this is a relatively stable implosion, based on the criterion expressed by Eq. (1) that IFAR ≈ 16 would correspond to a marginally stable case. The general agreement in size and shape between the measured and simulated radiographs indicates that the shell has imploded without major disruption. If there had been significant instability and disruption of the shell during its implosion, it is likely that a significantly large amount of shell CH would have been mixed into the DT shell, creating a much stronger shell shadow without the distinctly limb-darkened appearance characteristic of a thin, intact CH shell remnant.

This shot 81590 implosion was simulated with the 2-D radiation–hydrodynamic code *DRACO* [47] to simulate the multibeam nonuniformity effects of the 60-beam OMEGA irradiation distribution. *DRACO* includes full 3-D laser ray tracing of the laser light [34], including the effects of CBET [36], collisional absorption of laser energy via inverse bremsstrahlung [35], a nonlocal, multigroup heat-conduction model [48], and a multigroup diffusive radiation transport with Astrophysical Opacity tables [37]. The *Spect3D* radiograph based on this simulation is superimposed on the plot in Fig. 6(b) as the dotted–dashed curve. The further effects of the small-scale single-beam speckle nonuniformity are included in *DRACO* simulations still in progress. The simulated radiograph is obtained from a viewing direction that is 30° out of the equatorial plane. The 2-D geometry and (r, z) cylindrical coordinates of *DRACO*

impose an artificial axial symmetry that drastically affects the simulated images when viewed from certain directions. A polar view angle of 30° from the equatorial plane was selected—a direction halfway in solid angle between the polar and equatorial directions—as a way to minimize the appearance of structural coherence imposed by the axial symmetry. Figure 6(b) shows that the 2-D effects of the large-scale multibeam nonuniformity broaden the shadow edges, in slightly better agreement with the measured radiograph. While the *LILAC* simulation appears to have reproduced the amount of remnant CH closely, the *DRACO* simulation has predicted a smaller amount of remnant CH.

The full image plane of the *DRACO/Spect3D* radiograph is shown in Fig. 7(a); the measured radiograph is plotted again in Fig. 7(b) for comparison. The former was simulated with a flat backlighter, and the latter has its original shaped backlighter profile. Both images and the density profiles in Fig. 7(c) have dashed $100\text{-}\mu\text{m}$ -radius rings superimposed to facilitate comparison. In the *DRACO* cryogenic implosion simulation, multibeam illumination nonuniformity seeds ablation-surface perturbations that grow and appear as ripples on the DT shell/core interface and on the CH remnant surface in Fig. 7(c). The implosion is mirror symmetric about the equatorial plane, and the z axis is the cylindrical symmetry axis. The upper quadrant shows the total mass density, and the lower quadrant shows only the CH mass density so that the rippled DT/CH surface can be seen more clearly. These ripples broaden the edges of the simulated radiographic shadow, significantly improving the agreement of the apparent scale lengths of the shadow edges. The effects of other perturbation sources on radiographs are currently under investigation.

The possibility of the jetting [44] or turbulent mixing of the ablator material into the DT, leaving a small fraction of a percent atomic contamination of C in unstable implosions drastically

increases the measured radiographic absorption over and above that which can be accounted for in a “clean” 1-D simulations. A lineout of the measured radiograph of OMEGA shot 70535, reported in [28], is plotted (solid curve) in Fig. 8. A 1-D *LILAC/Spect3D* simulation of this shot is shown as the dotted curve in Fig. 8, superimposed on the measured radiograph at the same convergence ($CR \approx 4$). The radiograph was simulated without self-emission. This experiment was conducted earlier in our radiography project when the exposure time was 200 ps, as compared with the 40-ps exposure time used currently, which has effectively reduced the recorded self-emission in more recent radiographs by a factor of 5. Consequently, the time-integrated self-emission appears as bright as the backlighter, even though the radiograph was taken at a time of low convergence. The measured radiograph shows much more absorption than the simulated radiograph. Most likely, CH polymer from the original ablator layer has moved into the DT ice at some point in the implosion. The dotted-dashed and dashed curves in Fig. 8 show the simulation results obtained if 0.1% and 0.2% C, respectively, are added to the initial DT composition. A visual comparison suggests that a uniform $\approx 0.2\%$ C contamination is consistent with the measured radiograph. The absorption by this very small trace of C in the DT indicates clearly that mix has taken place and that the amount of mix can be estimated. In this particular radiograph, it appears that the mix has been fairly uniform, up to the spatial resolution length of the image. The measured attenuation also appears to be in the optically thin range. The absorption by C concentrated in spatially unresolved, optically thick CH fragments would be partially saturated, resulting in less attenuation per C atom than with unsaturated, optically thin linear absorption. Consequently, the C concentration of 0.2% inferred assuming uniform mix is a lower limit, considering the possibility of saturated absorption by localized optically thick concentrations of C.

Radiographic mix measurements complement other mix measurements based on enhanced core x-ray emission [49] and shell-dopant x-ray line emission [50,51]. Core emission also provides quantitative measurements of mix that associate hydrodynamic instability with low values of the adiabat parameter α [9], which can be understood in terms of the simple properties of cryogenic isobaric stagnated implosion cores [52,53].

Since CH contaminant passes through the DT ice layer on its way to the core, associating lower α values with core contamination implies a similar association with contamination of the DT ice layer as well, in the manner of Fig. 8. A few more examples will illustrate this trend: The radiographs in Fig. 9(a) at $\alpha \approx 2.5$ and Fig. 9(b) at $\alpha \approx 2.0$ show excess absorption, while the radiograph of the more-stable implosion in Fig. 9(c) at $\alpha \approx 4.0$ shows no mix-enhanced absorption. The results of shot 81590 in Fig. 6 show no sign of uniform mix in the DT adding noticeably to the already strong absorption by the thin, intact CH remnant, although the comparison of its simulated and measured radiographs exhibits the effect of short-scale perturbations. This is, incidentally, an example where perturbations and mix do not necessarily go hand in hand. The adiabat of shot 70535 in Fig. 9(a) is $\alpha \approx 2.5$, the same as shot 81590, but it shows signs of mix, which indicates instability. The IFAR of shot 70535 is 17, slightly higher than the $\text{IFAR}_{\text{boundary}}$ value of 16.4 for this adiabat, according to Eq. (1), while the IFAR of shot 81590 is significantly lower at $\text{IFAR} \sim 10$ than this boundary-criterion value [4], which is consistent with mix occurring in the former, but not the latter. By this same criterion, shot 80543 with $\text{IFAR} = 20$ in Fig. 9(b) should be unstable, and shot 75372 in Fig. 9(c) should be stable, both of which are consistent with the former exhibiting excess absorption, indicating instability, and the latter showing no excess absorption, indicating stability.

5. Scaling soft x-ray radiography to higher convergence

Free–free (FF) absorption is the dominant process accounting for the radiographic shadow of a pure DT shell. The strong sensitivity of the FF radiographic optical thickness τ_{FF} of a DT shell can be represented approximately in terms of its mass M_{shell} , radius R , nuclear charge Z , and atomic mass A as

$$\tau_{\text{FF}} \propto \frac{Z^2 (M_{\text{shell}}/A)^2}{R^5 \nu^3} \quad (7)$$

at spectral energy ν (neglecting the Planck constant and other atomic constants, which do not enter into this scaling expression), assuming a fixed IFAR and full ionization. The FF opacity is proportional to the shell areal density squared, so at fixed IFAR, the optical thickness varies as the fifth power of the radial convergence, in contrast with the BF opacity, which varies roughly linearly with density, at constant ionization [26], resulting in

$$\tau_{\text{BF}} \propto \frac{Z^4 (M_{\text{shell}}/A)}{R^2 \nu^3}. \quad (8)$$

Bound–free absorption dominates the radiographic signal of C. The optical thicknesses from both processes are inversely proportional to the cube of the spectral energy. In designing a radiography experiment, selecting a backlighter spectral energy ν that keeps the optical thickness near the optimum $\tau \approx 1$ requires raising the spectral energy as the $-5/3$ power of the

shell radius as one follows the implosion toward stagnation. These spectral and convergence dependences are very strong. If one tunes the spectral energy to achieve the ideal $\tau_{\text{FF}} \approx 1$ at a particular shell radius R , the radiographic absorption becomes saturated ($\tau \approx 3$) when the shell has converged only as far as $0.8 R$. This makes it difficult to design flexible experiments since even small variations in implosion performance or timing can put one out of the optimum radiographic dynamic range.

This scaling difficulty is illustrated by the contour plot in Fig. 10, showing the central attenuation of a *DRACO/Spect3D* simulation of the cryo implosion shot 47206 as a function of spectral energy and time. This implosion was an earlier milestone achievement with a record areal density of 202 mg/cm^2 [22,54]. The ideal range of optical thicknesses for sensitive radiographic response is midway between transparency and saturation, near $\tau \approx 1$, giving very roughly an attenuation range from 0.2 to 0.6, which corresponds on the gray-scale map to a very narrow band where white changes to light gray. At any fixed time, this represents a spectral range of no more than about 100 eV. This very narrow spectral range moves very rapidly in time. Dashed horizontal lines have been placed at the spectral energies of the Si Ly_α and He α spectral lines, which, according to Fig. 10, are suitable for radiography at about 100 ps before stagnation or perhaps earlier, considering that limb-darkened attenuation is higher than the central attenuation and will reach the ideal value slightly earlier. The optimum spectral energy for radiography of this implosion at stagnation would be near 2.4 keV, corresponding to the He α line of S.

Core self-emission can be examined further, using the expression for the FF emissivity of pure DT [26]:

$$\varepsilon_{\nu}^{\text{FF}} = \frac{8}{3} \sqrt{\frac{\pi}{3}} \alpha_{\text{FS}}^3 \chi_{\text{H}} \alpha_0^3 \left[\frac{P}{kT} \right]^2 g_{\text{FF}} \left(\frac{\chi_{\text{H}}}{kT} \right)^{1/2} e^{-h\nu/kT}. \quad (9)$$

The fine structure (FS) constant is written as α_{FS} to distinguish it from the in-flight shell adiabat parameter α , and χ_{H} is the hydrogen ground-state ionization energy. This expression is written in terms of pressure P rather than a density quantity because the stagnated cores of cryogenic implosions are isobaric, to a good approximation [55]. The dominant spectral dependence of FF emissivity is the exponential factor $e^{-h\nu/kT}$, modified slightly by the spectral and temperature dependence of a Gaunt factor [39]. Consequently, the ideal backlighting energy should be as high as possible to reduce the self-emission background, but not so high that the ν^{-3} scaling of τ_{FF} in Eq. (7) makes the shell too transparent. As illustrated in the Figs. 3(b) and 5 radiographs, self-emission is separate from the ice shell shadow. It forms an interfering background if it is blurred by finite spatial resolution or nonradial fluid motion. The emissivity ε_{FF} acquires a radial dependence through its dependence on the radial temperature distribution $T(r)$. If possible, we would like to use these properties of the temperature profile and the FF emissivity to keep the core self-emission as far from the ice shell shadow as possible.

A simple analysis based on Eq. (9) shows that higher backlighter spectral energies increase the separation between the core self-emission and the ice shell shadow. R. Betti *et al.* have shown that isobaric core temperature profiles drop off rapidly toward the edge of the core as [55]

$$T(r) = T_{\text{center}} \left[1 - (r/R)^2 \right]^{2/5}. \quad (10)$$

Under core conditions relevant to soft x-ray radiography, we have $h\nu/kT \approx 1$ near the center. Toward the edge of the core, the temperature drops rapidly, giving $h\nu/kT \gg 1$, and the FF emissivity of the core, dominated by the exponential factor $\exp(-h\nu/kT)$, eventually drops as r approaches R . This behavior allows the self-emission to be moved farther from the ice shell, perhaps to significant advantage.

To illustrate this, we postulate an isobaric sphere of radius R surrounded by a thin homogeneous ice layer of thickness $\Delta R = R/10$ at the time a radiograph is measured, not to be confused with the IFAR, which refers to a time at the beginning of the acceleration phase of the implosion. We assume that the radiographic optical thickness at the point of maximum limb darkening on the radiograph, $r = R$, is $\tau_{\text{max}} = 1$. Assuming a uniform shell opacity κ , the optical thickness at the center $r = 0$ of the radiograph is

$$\tau_{\text{center}} = \kappa 2\Delta R \quad (11)$$

and the maximum limb-darkened optical thickness is

$$\tau_{\text{max}} = \kappa (8R\Delta R)^{1/2} \quad (12)$$

in the thin-shell limit. The imaged intensity distributions of the core self-emission, modified by the thin DT shell, are shown in Fig. 11, plotted in units of the shell radius R as functions of the

image radius. The intensity is normalized to be 1.0 for the $h\nu/kT = 0.5$ image at $r = 0$. This normalization effectively fixes the core temperature and pressure, leaving $h\nu/kT$ as the one free parameter.

The self-emission profiles in Fig. 11 drop farther from the core/ice interface at higher $h\nu/kT$ a value, which anticipates another possible benefit of increasing the backlighter energy. To show this radial cutoff more clearly, a square marker is placed on each self-emission profile curve at the point where the intensity has dropped to $1/e$ of the central value. Working near $h\nu/kT \approx 1$ with a $40\text{-}\mu\text{m}$ -radius core, as in the present work, the self-emission radius is within $2.5\text{ }\mu\text{m}$ of the core edge, which is too close to be resolved at the current $15\text{-}\mu\text{m}$ resolution. If we can tolerate the loss of absorption from raising the backlighter energy to $h\nu/kT = 2$, the self-emission could be moved about $8\text{ }\mu\text{m}$ away, which would extend the useful range of soft x-ray radiography closer to stagnation. This analysis relies on the isobaric stagnation assumption, so it becomes questionable at times before stagnation, but it suffices to illustrate another way to improve x-ray radiographs of ICF implosions by raising the backlighter energy.

We have been dealing with the radiative properties of hydrogen (H, D, T) and C at soft x-ray energies, where strong spectral dependence requires a precise backlighter energy specification and strong composition dependence allows trace contamination to strongly alter the radiographs. These properties are illustrated in Fig. 12, which shows the mass-absorption coefficients of D (solid curve) and C (dashed curve) plotted as functions of spectral energy for two sets of conditions: (1) D at $\rho = 3\text{g/cm}^3$, $kT = 25\text{ eV}$, and (2) C at $\rho = 0.5\text{g/cm}^3$, $kT = 100\text{ eV}$. These values represent, respectively, the conditions in the center of a DT-ice shell and in the outer tail of the shell mass distribution where unablated C might remain, both at times

approaching stagnation. These values suffice for illustrating the distinguishing properties of (H, D, T) and C. The shaded band just below 2.0 keV indicates where soft x-ray radiography was used, and the band from 50 to 80 keV indicates where Compton radiography was used [23]. The scaling of the optical thickness of shells of these materials can be written to a good approximation for shells of mass M_{shell} , radius R , nuclear charge Z , and atomic mass A as in Eq. (7) for FF absorption, which is dominant for hydrogen isotopes; Eq. (8) for BF absorption, which is dominant for C; and

$$\tau_{\text{C}} \propto \left(\frac{Z}{A} \right) \frac{M_{\text{shell}}}{R^2}, \quad (13)$$

for Compton radiography at backlighter energies above a few tens of keV, where Compton scattering is expected to dominate all other absorption processes. Equations (7), (8), and (13) show the main distinctions between the three different absorption mechanisms. Many effects and parameters, such as shell geometry and aspect ratio, the relative abundance of C, etc., remain to be considered in constructing fully quantitative expressions applicable to specific cases. The most important features are the fifth-order scaling of τ_{FF} with R , resulting from the second-order density dependence of the FF opacity and emissivity; the relatively strong fourth-order Z dependence of τ_{BF} , resulting from the strong charge dependence of the photoionization cross section; and the almost complete absence of material and spectral dependence of τ_{C} . Compton scatter can be described by an effective absorption coefficient. Even though Compton-scattered photons are not actually absorbed, they are removed by the object from the backlighter flux, just as effectively as if they had been actually absorbed. The spectral dependence of Compton scatter

is that of the Klein–Nishina cross section [56], which is very weak for backlighter energies in the tens-of-keV range, where it is expected to dominate all other absorption processes. Consequently, the interpretation of Compton radiographs do not depend on the backlighter spectrum nearly as sensitively as with FF and BF absorbers, where the energy dependence is third order in ν . With backlighter photon energies far in excess of atomic-scale energies, the Klein–Nishina cross section applies equally to each electron in the object, to an excellent approximation, independent of its initial state, i.e., whether it is bound or free. Also, the total number of electrons per mass in all atoms is very nearly the same, one per proton or nearly one per two nucleon masses, except for H and T. Consequently, Compton radiography measures an absorption profile that is related directly and accurately to the mass-density profile. In particular, trace contamination by CH that overwhelms the opacity of DT in soft x-ray radiography will have practically no effect on the effective Compton opacity.

The obvious disadvantage of Compton radiography, at least for OMEGA-scale implosions, is that the radiographic attenuation is at the several-percent level. This radiographic attenuation signal cannot be expected to produce images with useful detail. Low backlighter fluxes experienced in past experiments on OMEGA have barely sufficed to keep the photon noise of the radiographs from completely obscuring the attenuation signal. Nevertheless, weak absorption signals can be filtered with simple models to extract shell model parameter estimates near the time of stagnation [23]. If the spatial resolution of the imaging device allows many statistically independent measurements of an OMEGA Compton radiographic absorption distribution to be made, one can obtain shell parameter estimates that are much more accurate than the imprecision of an individual radiographic transmission value might suggest.

The success of a cryogenic implosion is most often evaluated in terms of a few key parameters, such as the areal mass density of the imploded shell,

$$\overline{\rho R} = \int_0^\infty \rho(r) dr. \quad (14)$$

It is possible to estimate the areal mass density accurately by fitting a parameterized shell model to a set of relatively inaccurate measurements. The suitable three-parameter model, illustrated in Fig. 13(a), is a hollow homogeneous shell characterized by inner and outer radii, R_1 and R_2 , and an opacity κ . These parameters are related to the areal density $\overline{\rho R}$ by

$$\overline{\rho R} = \frac{m_i}{Z\sigma_{\text{KN}}} \kappa (R_2 - R_1), \quad (15)$$

where m_i is the average ion mass; Z is the average number of electrons per ion, bound plus free; and σ_{KN} is the Klein–Nishina cross section at the backlighter energy. This simple model produces a limb-darkened shadow characteristic of a hollow shell. A radiograph obtained from this model is shown by the solid curve in Fig. 13(b), superimposed on a simulated Compton radiograph, shown as the dashed curve, obtained from a 1-D *LILAC/Spect3D* simulation of shot 55723 [22]—another OMEGA milestone implosion—setting a record measured peak areal density of 300 mg/cm² [8].

The important questions associated with this parameter estimation method are whether or not the areal-density estimate obtained in this way corresponds to its radial integral definition in Eq. (14) and whether or not the estimate is accurate.

In so far as Eq. (15) was obtained from Eq. (14) from the three-parameter model, the two are consistent. If the actual opacity (or density) profile departs substantially from the fitting model, the areal-density estimate based on fitting the model to the data may not be consistent with Eq. (14), but it is still a quantity that is well defined in terms of a straightforward procedure, a “radiographically averaged areal density,” to give it a name. The areal density most commonly measured in ICF implosions is based on the slowing of DT or DD nuclear reaction products, such as neutrons measured in time-of-flight detectors, which involves an interpretive step based on assumed mass distributions that are not necessarily spherically symmetric and/or particle paths that are not necessarily radial, so it is standard procedure to refer to the method of measurement when quoting areal-density measurements.

We apply the method of maximum-likelihood, least-squares parameter estimation [57] using the three-parameter model illustrated in Fig. 13(a) to a sequence of radiographs covering a 180-ps interval, including the time of stagnation, of a *LILAC/Spect3D* simulated cryogenic OMEGA implosion (shot 55723). This sequence is plotted in Fig. 14(a) once every 20 ps, shows the rapid increase in attenuation that occurs during the final approach to stagnation. The areal density of the imploded shell, calculated from the simulated density profiles using Eq. (16), is plotted as the curve in Fig. 14(b). The data points superimposed on the areal density curve are the areal-density estimates obtained from the fit of the three-parameter model to the simulated radiographs. The radial radiograph traces in Fig. 14(a) correspond to data points in Fig. 14(b) by matching the line format. The final two data points in Fig. 14(b) are not represented in Fig. 14(a).

The areal-density estimates are in nearly perfect agreement with the simulated values, which confirms the validity of the fitting model over the entire time interval shown. The error bars are the variances of the areal-density estimates, based on the assumption that the radiographic transmission has been measured to within an absolute $\delta Tr \approx 5\%$ accuracy and that the spatial resolution is $\delta r_{BL} \approx 5\mu\text{m}$. These represent relative errors of about $\frac{\delta \overline{\rho R}}{\overline{\rho R}} \approx 16\%$. Remarkably, the relative variance of the areal-density estimate varies little over the entire interval, while attenuation ranges from close to the measurement error of $\sim 5\%$ at the start of this interval to $\sim 15\%$ at the end. One might expect parameter estimate variances to be larger earlier in time when the transmission signal is closer to the noise level, but that is also when the radiograph covers a larger area of the image plane, allowing one to measure a larger number of statistically independent transmissions. This analysis is linear, so the parameter estimate variances are linear with respect to the transmission measurement variance δTr and with respect to the reciprocal of the square root of the number of data points, giving

$$\frac{\delta \overline{\rho R}}{\overline{\rho R}} \leq 16\% \left(\frac{\delta Tr}{Tr} \right) \left(\frac{\delta r_{BL}}{5\mu\text{m}} \right). \quad (16)$$

This indicates that important properties of the stagnated shell can be inferred from OMEGA experimental data, so it remains an important option, or at least an alternative against which the feasibility of soft x-ray radiography can be compared.

6. Conclusions

The in-flight characteristics of converging cryogenic DT shells have been observed with monochromatic soft x-ray radiography on OMEGA. A crystal imager was used for short-pulse (20-ps), monochromatic x-ray backlighting (1.865 keV) of 60-beam OMEGA DT cryogenic implosions. Radiographs of the converging DT shell and the unablated trace of the CH polymer shell in some implosions provide diagnostics of implosion dynamics and mix. The level of mixing of the CH ablator with the DT ice has been inferred in unstable, low-adiabat implosions. We continue to make progress against the known limitations of soft x-ray radiography imposed by hot-spot self-emission. We are working on finer spatial resolution and brighter backlighters, which are the primary limitations on soft x-ray radiography. In the future development of this technique, the advantages of harder backlighters must be balanced against the loss of radiographic absorption at higher spectral energy. The limit of hard-photon backlighting is Compton radiography, where the transmission signal of OMEGA-scale targets is very weak, but it is almost completely independent of the backlighter spectrum and material composition; also there is effectively no background caused by self-emission. As a mass-distribution diagnostic, almost all ambiguities are eliminated, yielding important measurements of areal density, and it is under active consideration as we work to develop ICF implosion radiography in the future.

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REFERENCES

- 1) R.S. Craxton, K.S. Anderson, T.R. Boehly, et al., Phys. Plasmas **22**, 110501 (2015).
- 2) J. Nuckolls, L. Wood, A. Thiessen, et al., Nature **239**, 139–142 (1972).
- 3) V.N. Goncharov, S.P. Regan, E.M. Campbell, et al., Plasma Phys. Control. Fusion **59**, 014008 (2017).
- 4) V.N. Goncharov, T.C. Sangster, R. Betti, et al., Phys. Plasmas **21**, 056315 (2014).
- 5) C. Stoeckl, C. Chiritescu, J.A. Delettrez, et al., Phys. Plasmas **9**, 2195–2201 (2002).
- 6) F.J. Marshall, R.S. Craxton, J.A. Delettrez, et al., Phys. Plasmas **12**, 056302 (2005).
- 7) V.N. Goncharov, T.C. Sangster, P.B. Radha, et al., Phys. Plasmas **15**, 056310 (2008).
- 8) T.C. Sangster, V.N. Goncharov, R. Betti, et al., Phys. Plasmas **17**, 056312 (2010).
- 9) T.C. Sangster, V.N. Goncharov, R. Betti, et al., Phys. Plasmas **20**, 056317 (2013).
- 10) S.P. Regan, V.N. Goncharov, I.V. Igumenshchev, et al., Phys. Rev. Lett. **117**, 025001 (2016).
- 11) T.R. Boehly, D.L. Brown, R.S. Craxton, et al., Opt. Commun. **133**, 495–506 (1997).
- 12) E.M. Campbell, W.J. Hogan, Plasma Phys. Control. Fusion **41**, B39–B56 (1999); W.J. Hogan, E.I. Moses, B.E. Warner, et al., Nucl. Fusion **41**, 567–573 (2001); G.H. Miller, E.I. Moses, C.R. Wuest, Opt. Eng. **43**, 2841–2853 (2004); E.I. Moses, J. Phys.: Conf. Ser. **112**, 012003 (2008).
- 13) J.D. Lawson, Proc. Phys. Soc. Lond. B **70**, 6–10 (1957).
- 14) A. Bose, K.M. Woo, R. Betti, et al., Phys. Rev. E **94**, 011201(R) (2016).
- 15) J.D. Lindl, Phys. Plasmas **2**, (1995) 3933–4024; J.D. Lindl, P. Amendt, R.L. Berger, et al., Phys. Plasmas **11**, 339–491 (2004).

- 16) O.A. Hurricane, D.A. Callahan, D.T. Casey, et al., *Nature* **506**, 343–348 (2014).
- 17) R. Betti, A.R. Christopherson, B.K. Spears, et al., *Phys. Rev. Lett.* **114**, 255003 (2015).
- 18) C. Stoeckl, R. Epstein, R. Betti, et al., *Phys. Plasmas* **24**, 056304 (2017).
- 19) V.N. Goncharov, T.C. Sangster, T.R. Boehly, et al., *Phys. Rev. Lett.* **104**, 165001 (2010).
- 20) F.J. Marshall, P.W. McKenty, J.A. Delettrez, et al., *Phys. Rev. Lett.* **102**, 185004 (2009).
- 21) R. Epstein, V.A. Smalyuk, F.J. Marshall, et al., *Bull. Am. Phys. Soc.* **54**, 306 (2009).
- 22) X-ray radiography of cryogenic implosions on OMEGA, LLE Review Quarterly Report, Laboratory for Laser Energetics, University of Rochester, Rochester, NY, LLE Document No. DOE/NA/28302-964, **123**, 128–144 (2010).
- 23) R. Tommasini, A. MacPhee, D. Hey, et al., *Rev. Sci. Instrum.* **79**, 10E901 (2008); National Laser Users’ Facility and external users’ programs, LLE Review Quarterly Report, Laboratory for Laser Energetics, University of Rochester, Rochester, NY, LLE Document No. DOE/NA/28302-910, **120**, 218–267 (2009); R. Tommasini, S.P. Hatchett, D.S. Hey, et al., *Phys. Plasmas* **18**, 056309 (2011).
- 24) S. Skupsky, J. A. Marozas, R. S. Craxton, et al., *Phys. Plasmas* **11**, 2763 (2004); P.B. Radha, F.J. Marshall, et al., *Phys. Plasmas* **20**, 056306 (2013).
- 25) D.G. Hicks, B.K. Spears, D.G. Braun, et al., *Phys. Plasmas* **17**, 102703 (2010).
- 26) H.R. Griem, *Principles of Plasma Spectroscopy*, Cambridge University, Cambridge, England, 1997.
- 27) L.J. Waxer, D.N. Maywar, J.H. Kelly, et al., *Opt. Photonics News* **16**, 30–36 (2005).
- 28) C. Stoeckl, M. Bedzyk, G. Brent, et al., *Rev. Sci. Instrum.* **85**, 11E501 (2014).
- 29) D.K. Bradley, P.M. Bell, O.L. Landen, et al., *Rev. Sci. Instrum.* **66**, 716–718 (1995).
- 30) J.A. Oertel, T. Archuleta, C.G. Peterson, et al., *Rev. Sci. Instrum.* **68**, 789–791 (1997).

- 31) C. Stoeckl, R. Boni, F. Ehrne, et al., *Rev. Sci. Instrum.* **87**, 053501 (2016).
- 32) R.N. Bracewell, *The Fourier Transform and Its Applications*, 3rd ed., McGraw-Hill, Boston, 2000.
- 33) J. Delettrez, R. Epstein, M.C. Richardson, et al., *Phys. Rev. A* **36**, 3926–3934 (1987).
- 34) J. A. Marozas, F. J. Marshall, R. S. Craxton, et al., *Phys. Plasmas* **13**, 056311 (2006).
- 35) S. Atzeni, J. Meyer-ter-Vehn, *The Physics of Inertial Fusion: Beam Plasma Interaction, Hydrodynamics, Hot Dense Matter*, International Series of Monographs on Physics, Clarendon, Oxford, 2004, pp. 47-50.
- 36) I. V. Igumenshchev, D. H. Edgell, V. N. Goncharov, et al., *Phys. Plasmas* **17**, 122708 (2010).
- 37) N. H. Magee, Jr., J. Abdallah, Jr., R. E. H. Clark, et al., "Atomic Structure Calculations and New Los Alamos Astrophysical Opacities", *Astronomical Society of the Pacific Conference Series (Astrophysical Applications of Powerful New Databases*, S. J. Adelman and W. L. Wiese eds.) **78**, 51 (1995); W. F. Huebner, A. L. Merts, N. H. Magee, Jr., M. F. Argo, *Astrophysical Opacity Library*; Los Alamos Report LA-6760-M.
- 38) J.J. MacFarlane, I.E. Golovkin, P. Wang, et al., *High Energy Density Phys.* **3**, 181–190 (2007); Prism Computational Sciences, Inc., Madison, WI 53711.
- 39) J.A. Gaunt, Continuous absorption, *Proc. R. Soc. Lond. A* **126**, 654–660 (1930); W.J. Karzas, R. Latter, Electron radiative transitions in a coulomb field, *Astrophys. J. Suppl. Ser.* **6**, 167–212 (1961).
- 40) S. Atzeni, J. Meyer-ter-Vehn, *The Physics of Inertial Fusion: Beam Plasma Interaction, Hydrodynamics, Hot Dense Matter*, International Series of Monographs on Physics, Clarendon, Oxford, 2004, p. 345.

- 41) I.V. Igumenshchev, V.N. Goncharov, F.J. Marshall, et al., *Phys. Plasmas* **23**, 052702 (2016).
- 42) F.J. Marshall, J.A. Delettrez, R. Epstein, et al., *Phys. Plasmas* **11**, 251–259 (2004).
- 43) I.V. Igumenshchev, F.J. Marshall, J.A. Marozas, et al., *Phys. Plasmas* **16**, 082701 (2009).
- 44) I.V. Igumenshchev, V.N. Goncharov, W.T. Shmayda, et al., *Phys. Plasmas* **20**, 082703 (2013).
- 45) S.X. Hu, V.N. Goncharov, P.B. Radha, et al., *Phys. Plasmas* **17**, 102706 (2010).
- 46) S.X. Hu, D.T. Michel, A.K. Davis, et al., *Phys. Plasmas* **23**, 102701 (2016).
- 47) D. Keller, T. J. B. Collins, J. A. Delettrez, et al., *Bull. Am. Phys. Soc.* **44**, 37 (1999);
P. B. Radha, V. N. Goncharov, T. J. B. Collins, et al., *Phys. Plasmas* **12**, 032702 (2005).
- 48) D. Cao, G. Moses, and J. A. Delettrez, *Phys. Plasmas* **22**, 0823208 (2015).
- 49) T. Ma, P.K. Patel, N. Izumi, et al., *Phys. Rev. Lett.* **111**, 085004 (2013).
- 50) B. A. Hammel, H.A. Scott, S.P. Regan, et al., *Phys. Plasmas* **18**, 056310 (2011).
- 51) S.P. Regan, R. Epstein, B.A. Hammel, et al., *Phys. Plasmas* **19**, 056307 (2012); S.P. Regan, R. Epstein, B.A. Hammel, et al., *Phys. Rev. Lett.* **111**, 045001 (2013).
- 52) S.Y. Gus'kov, O.N. Krokhin, V.B. Rozanov, *Nucl. Fusion* **16**, 957 (1976).
- 53) R. Epstein, V.N. Goncharov, F.J. Marshall, et al., *Phys. Plasmas* **22**, 022707 (2015).
- 54) T.C. Sangster, V.N. Goncharov, P.B. Radha, et al., *Phys. Rev. Lett.* **100**, 185006 (2008).
- 55) R. Betti, M. Umansky, V. Lobatchev, et al., *Phys. Plasmas* **8**, 5257–5267 (2001);
R. Betti, K. Anderson, V.N. Goncharov, et al., *Phys. Plasmas* **9**, 2277–2286 (2002); V.N. Goncharov, Direct-drive inertial fusion: Basic concepts and ignition target designing, in: *Laser-Plasma Interactions*, D.A. Jaroszynski, R. Bingham, R.A. Cairns (Eds.), Scottish Graduate Series, CRC, Boca Raton, FL, 2009, pp. 409–418.

- 56) E. Segre, Nuclei and Particles, W. A. Benjamin, New York, 1964, p. 54.
- 57) P.R. Bevington, D.K. Robinson, Data Reduction and Error Analysis for the Physical Sciences, 3rd ed., McGraw-Hill, Boston, 2003.

FIGURE CAPTIONS

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 to 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, CE, or doped-CD ablator coated on the inside with a 50- to 75- μm -thick DT cryogenic ice layer.

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 .

Fig. 3. Radiograph simulation: The (a) *LILAC* profiles and (b) *Spect3D* radiograph of an OMEGA cryogenic implosion at $\text{CR} \approx 11$ are shown. This radiograph was simulated assuming a Si He $_{\alpha}$ backlighter pulse (1865 eV) and perfect spatial resolution. The imploding shell consists of an inner DT ice peak, around radius 40 μm , and an unablated remnant of the CH shell near radius 100 μm at a density between one and two orders of magnitude lower than the peak density. Each of these two shell features casts a distinct shadow in the radiograph (b), where the

attenuated backlight intensity (dashed curve) and the core self-emission (dotted–dashed curve) combine to form the total simulated radiograph (solid curve).

Fig. 4. Simulated implosion and radiographs of OMEGA shot 81590: (a) The trajectory of the shell [peak density trajectory (solid curve) within the shaded area between the inner and outer $1/e$ -density radius trajectories (left scale)] superimposed on the laser power (TW, dashed curve, right scale), areal density ρR (g/cm³, dotted–dashed curve, right scale), and the monochromatic self-emission flux at 1865 eV (dot–dot–dashed curve, arbitrary units). (b) *Spect3D* simulations of the radiographs at the four times indicated by line-format-coded arrows in (a).

Fig. 5. Radial lineouts of *LILAC/Spect3D* simulated radiographs of a cryogenic implosion: The dashed curves show the absorption of the DT and CH shell, the dotted–dashed curves show the self-emission, from the core, and the solid curves show the combination of both effects. The top arrows indicate the location of the minimum-transmission feature from the DT shell with self-emission, and the bottom arrows indicate the minimum absorption without self-emission. (a) The radiograph at $CR \approx 10$, where the real and apparent DT features coincide. Later, at $CR \approx 16$, (b) the spatial resolution of $\sim 15 \mu\text{m}$ has allowed the self-emission to obscure the actual absorption feature, while (c) shows the recovery of this feature at an improved resolution of $8 \mu\text{m}$.

Fig. 6. Backlit image of cryogenic implosion shot 81590: (a) The measured backlit image of the implosion; (b) the backlighter shape-corrected horizontal lineout (solid) of the simulated radiograph, compared to a *LILAC/Spect3D* simulation (dashed) and 2-D *DRACO/Spect3D*

simulation (dotted–dashed). The *LILAC/Spect3D* radiograph suggests that the amount of unablated CH was simulated correctly, and the *DRACO/Spect3D* radiograph reproduces the broader observed CH concentration gradient scale length at the CH/DT interface.

Fig. 7. *DRACO/Spect3D* simulation results: The *DRACO/Spect3D* simulated radiograph of shot 81590 shown in (a) represents the same time as the backlighter shape–corrected measured radiograph in (b). The meridional section of the *DRACO* total mass density profile is plotted in (c) in the upper quadrant with the CH contribution plotted in the lower quadrant. The rippling of the CH/DT interface is seen, showing that the 2-D effect produces a broadened average CH concentration profile that partially explains the broadened transmission profile of the measured radiograph, shown in Fig. 6(b).

Fig. 8. Evidence of ice/ablator mix: The backlighter shape–corrected lineout of shot 70535 the radiograph of a cryogenic target shown in [28] (solid curve) compared to a *Spect3D* post-processed *LILAC* simulation (dotted curve) with an additional simulation with 0.1% (dotted–dashed curve) and 0.2% (dashed curve) C, by atom, mixed uniformly into the DT. This shows that the measured radiograph is not consistent with pure DT, but rather with a uniform mix of 0.2% C into the DT.

Fig. 9. Measured association of ice/ablator mix with low shell adiabat: Backlighter shape–corrected radiograph lineouts from three cryogenic target experiments are compared to *Spect3D* post-processed *LILAC* simulations. Mixing of ablator material is required to match the

experimental data for a Ge-doped low-adiabat shots (a) 70535 ($\alpha = 2.5$) and (b) 80543 ($\alpha = 2.0$), but not for (c) a high-adiabat ($\alpha = 4.0$) implosion (shot 75372).

Fig. 10. Radiographic absorption over time and spectral energy: The attenuation of radiation escaping the center of a simulated imploding target is plotted as a function of time and spectral energy. The Ly_α and He_α lines of the Si backlighter are indicated by dashed lines. The areas of near-total extinction and near-total transparency are separated by a narrow band of attenuation (0.2 to 0.6) where radiography will be useful. This illustration is based on a *DRACO/Spect3D* simulation of OMEGA shot 47206, which reached a measured peak areal density of $\rho R = 202 \text{ mg/cm}^2$ [54].

Fig. 11. Radial self-emission profiles: An analytic approximation for the monochromatic x-ray intensity profile of a stagnated core is plotted versus its normalized radius r/R_{core} for various values of the spectral energy quantity $h\nu/kT$. The intensity is plotted in units of the central intensity of the $h\nu/kT = 0.5$ case. The core continuum drops rapidly with spectral energy. At the same time, the intensity profile moves farther from the core/DT-ice-shell interface, as indicated by the square symbols placed at the $1/e$ intensity point on the intensity profile curves.

Fig. 12. Absorption properties of the important ICF materials: The soft x-ray radiography of CH/DT cryogenic implosions is based on the very different absorption properties of C (dashed curve) and the isotopes of hydrogen [H, D, T (solid curve)], illustrated in this spectral plot of mass-absorption coefficients of D at $\rho = 3 \text{ g/cm}^3$, $kT = 25 \text{ eV}$ and C at $\rho = 0.5 \text{ g/cm}^3$, $kT =$

100 eV. These values represent, respectively, the conditions in the center of a DT-ice shell and in the outer tail of the shell mass distribution where unablated C might remain, both at times approaching stagnation. The light shaded band just below 2.0 keV indicates where soft x-ray radiography was used, and the band from 50 to 80 keV indicates where Compton radiography was used.

Fig. 13. A simple three-parameter shell model for analyzing Compton radiographs: This model is illustrated in (a). Even when detailed opacity profiles cannot be inferred accurately from the weak Compton radiographic signals, key performance parameters, such as the areal density, can be estimated by fitting simple models to measured radiographs. The *LILAC/Spect3D* simulation of a Compton radiograph of shot 55723 is plotted as the dashed curve (b) with the radiograph based on the model in (a), obtained using least-squares, best-fit parameters, plotted as the solid curve.

Fig. 14. Shell parameter estimates from simulated radiographic data: Accurate stagnation parameters can be inferred from the very weak Compton radiographic signal expected on OMEGA. (a) A sequence of *LILAC/Spect3D* radiographs covering a 180-ps interval, based on OMEGA shot 55723, is plotted once every 20 ps. (b) The areal density of the imploded shell is the curve plotted as a function of time. The data points are the areal-density estimates obtained from the maximum-likelihood weighted least squares fit of a three-parameter model to the simulated radiographs. The radial radiograph traces in (a) correspond to the data point error bars in (b) by line format. The point values are the areal-density estimates from the parameter fit, and the lengths of the error bars are the variances of these areal-density estimates, based on assuming

that the radiographic transmission has been measured to a 5% accuracy and that the spatial resolution is $5\text{ }\mu\text{m}$, indicated by the error bars inset in (a). The final two data points in (b) are not represented by curves in (a).

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(a)

(b)

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(a)

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(a)

(b)