

# The properties of hot-spot emission in a warm plastic-shell implosion on OMEGA

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A warm plastic-shell implosion was performed on the OMEGA laser system. The measured corona plasma evolution and shell trajectory in the acceleration phase are reasonably simulated by the one-dimensional *LILAC* simulation including the nonlocal and cross-beam energy transfer models. The results from analytical thin-shell model reproduce the time-dependent shell radius by *LILAC* simulation, and also the hot-spot x-ray emissivity profile at stagnation predicted by *Spect3D*. In the *Spect3D* simulations within a clean implosion, a “U”-shaped hot-spot radius evolution can be observed with the Kirkpatrick-Baez microscope response (the photon energy is from 4 to 8 keV). However, a fading away hot-spot radius evolution was measured in OMEGA warm plastic-shell implosion because of mixings. To recover the measured hot-spot x-ray emissivity profile at stagnation, a non-isobaric hot-spot model is built, and the normalized hot-spot temperature, density, and pressure profiles (normalized to the corresponding target-center values) are obtained.

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## I. INTRODUCTION

Two principal approaches (direct and indirect drive) are used with lasers to generate the energy flux and pressure required to drive inertial confinement fusion (ICF) [1]. In the direct-drive approach, a spherical target is illuminated directly with a number of individual laser beams [2, 3]. The laser energy is absorbed by the plasma ablating from the imploding capsule, and then is transferred into the central low-density region (hot spot). The main advantage of direct drive is the high coupling efficiency of the laser energy to kinetic energy of the shell (hydrodynamic efficiency  $\sim 4\%$  to  $6\%$ ). The highest hot-spot pressure achieved in OMEGA experiments is  $\sim 56$  Gbar with a neutron yield of  $\sim 5.3 \times 10^{13}$  [4, 5]. In the indirect-drive approach, the laser energy is absorbed and converted to x rays by a high-Z hohlraum that surrounds the target [6]. The main advantage of indirect drive is the reduced sensitivity of implosions to short-scale beam nonuniformities [1]. The highest hot-spot pressure achieved experimentally at the National Ignition Facility (NIF) is  $\sim 220$  Gbar in a so-called “high-foot” implosion with a neutron yield of  $\sim 9 \times 10^{15}$ , and a corresponding fuel gain of  $G_{fuel} > 2$  [7]. Here, the fuel gain is defined as the ratio of total thermonuclear energy production to the total energy delivered to the deuterium-tritium (DT) fuel. In both direct- and indirect-drive ICF, there are acceleration and deceleration phases. The acceleration phase ends when the laser is turned off and the shell starts traveling at approximately constant velocity. Multiple shock reflections off the incoming inner shell and an increase in gas pressure cause the deceleration phase to begin. During the deceleration phase, the compressing material

enclosed by the inner shell surface develops into a low-density, high-temperature region called the “hot spot” [8, 9].

Since thermonuclear ignition and high energy gain are the goals of ICF, one would naturally look to neutron yield as the primary measure of implosion performance [10]. The neutron yield depends on the hot-spot conditions. For DT implosions, the neutron yield is [11]:

$$Y = \langle \sigma_{DT} \rangle n_D n_T V t, \quad (1)$$

where  $Y$  is the neutron yield,  $\langle \sigma_{DT} \rangle$  is the DT reaction cross section,  $n_D$  and  $n_T$  are the D and T densities in the hot spot, respectively.  $V$  is the hot-spot volume, and  $t$  is the implosion confinement time. As a result, the hot-spot conditions, particularly the temperature ( $\langle \sigma_{DT} \rangle$  is most sensitive to the plasma temperature), play important roles in ICF. Neutron spectra, charged-particle spectra, and x-ray emission characteristics are also dependent on hot-spot conditions and can be used to infer them [6, 8, 10].

Measurements of continuum x-ray emission from the central hot spot of an ICF implosion can be directly related to hot-spot conditions using the relative dependence of continuum spectral emission rates on temperature and density or pressure [12]. It is reported that the free-free (FF) and bound-free (BF) emissivities of hot-spot hydrogen and carbon (by mixing) both scale as the square of the hot-spot pressure, with the assumption of a nominal temperature value [13]. In an unstable implosion, a trace amount of shell material mixed into the hot spot can increase the x-ray emission measurably because of the relatively high emissivity per atom of carbon

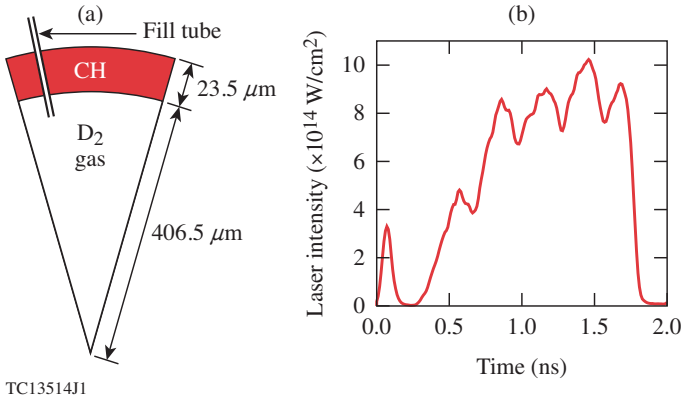


FIG. 1: (color online). (a) Target and (b) laser pulse intensity in the experiment. A fill tube of  $30\ \mu\text{m}$  outer diameter was used.

(or other shell materials) without significantly altering the DT concentration and the hot-spot conditions [14]. Consequently, measured hot-spot conditions and mixing mass were measured in both NIF and OMEGA implosions, based on the K-shell line emission of M-shell ionization species of higher-Z shell dopants [15–17]. Dopant line emission indicates mix originating from the doped shell layers only, while carbon continuum emission indicates fuel-shell mix originating from anywhere in the capsule shell. Recently, based on an isobaric implosion, a scaling of the total filtered x-ray emission as a constant power of the total neutron yield for implosions of targets of similar design over a broad range of shell implosion isentropes, has been proposed and has been confirmed by experiments [13, 14, 18, 19]. The pressure profile was obtained analytically based on a nominal temperature value, and a near-isobaric pressure was observed [13].

For this work, a warm plastic-shell implosion was performed on OMEGA, and the hot-spot emission properties were investigated. The radiative transfer code [20] *Spect3D* was used to simulate the hot-spot emission, while the one-dimensional (1D) hydrocode *LILAC* [21] was used to simulate the hot-spot conditions. In a clean implosion, a “U”-shaped hot-spot radius evolution was obtained with the Kirkpatrick-Baez microscope (KBFRAMED) response (the photon energy is 4 to 8 keV). However, in the experiment a fading away hot-spot radius trajectory was measured, which implies that an unstable implosion with significant mixing is involved. A non-isobaric hot-spot profile was built to recover the measured hot-spot radius. The normalized core pressure, temperature, and density profiles are inferred with this non-isobaric model.

## II. A WARM PLASTIC-SHELL IMPLOSION ON OMEGA

Figure 1(a) shows the target that was used in the experiment: a  $23.5\text{-}\mu\text{m}$ -thick,  $430\text{-}\mu\text{m}$ -outer-radius plastic (CH) shell and filled with  $\text{D}_2$  gas at pressures of 15 atm.

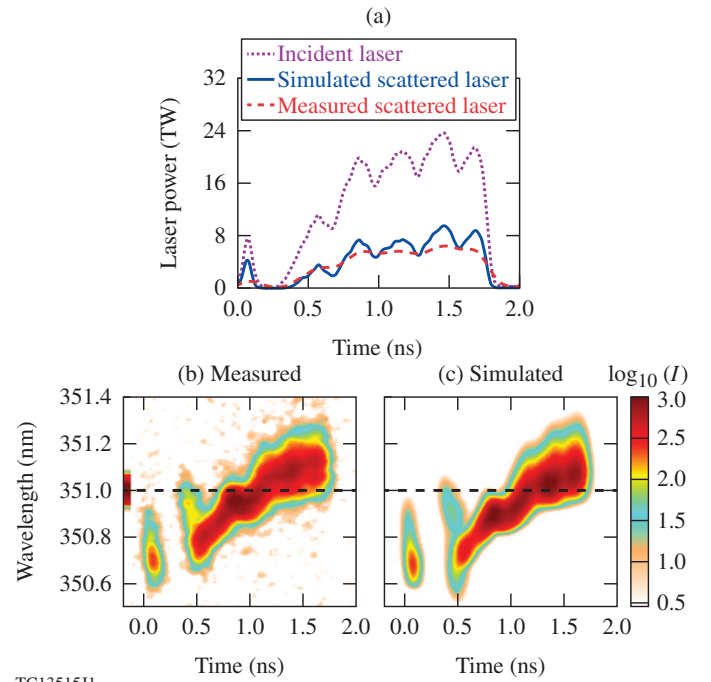
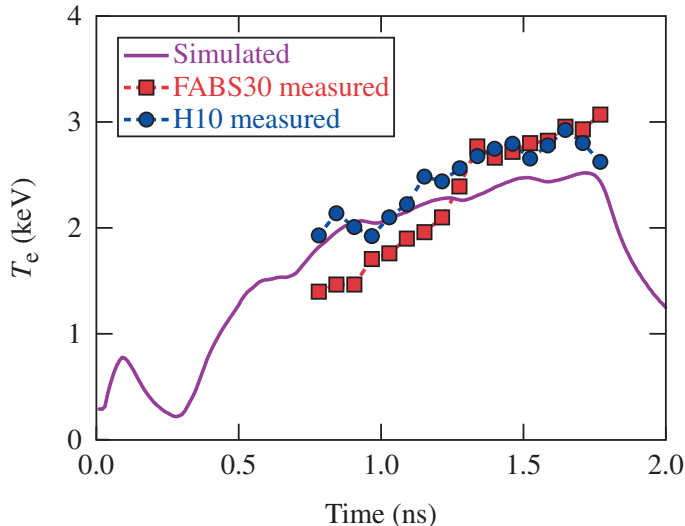


FIG. 2: (color online). (a) Measured (by the channel H13B) and simulated scattered light by *LILAC*; (b) Measured and (c) simulated scattered-light spectra.

The capsule was imploded by a 24-kJ relaxation-adiabat shaping UV laser pulse [22], which is shown in Fig. 1(b). The 351-nm-wavelength laser light was smoothed with polarization smoothing [23], distributed phase plates [24], and 1-THz-bandwidth smoothing by spectral dispersion (SSD) [25]. The shaped pulse comprised an  $\sim 80$ -ps full width at half maximum (FWHM) Gaussian prepulse (picket pulse) and a subsequent near-square pulse. The corresponding nominal laser intensity in the compression portion was  $\sim 8 \times 10^{14}\ \text{W}/\text{cm}^2$ . The picket pulse in front of the main pulse launched a shock wave that set the adiabat profile within the shell, which monotonically decreased from the outer ablation surface toward the inner shell surface, and an adiabat of  $\sim 3$  was achieved when the laser pulse was turned off. A slow-rising main pulse was designed to generate a relatively weak shock to meet the picket shock on the inner surface of the moving shell.

A 1D *LILAC* simulation was performed with the measured laser pulse, using the nonlocal thermal conduction and the cross-beam energy transfer (CBET) models [26, 27]. CBET caused by stimulated Brillouin scattering (SBS) reduces the absorption, making it possible for incoming light to bypass the highest absorption region near the critical radius. Direct-drive implosions are driven by a rocket effect that is generated by the absorption of laser light at  $10^{14} \sim 10^{15}\ \text{W}/\text{cm}^2$ , and CBET significantly reduces the performance of OMEGA direct-drive implosions [28].

Time-resolved scattered-light spectroscopy and time-integrated calorimetry are used on OMEGA to infer the absorption of light by the target [29]. Figure 2(a) com-

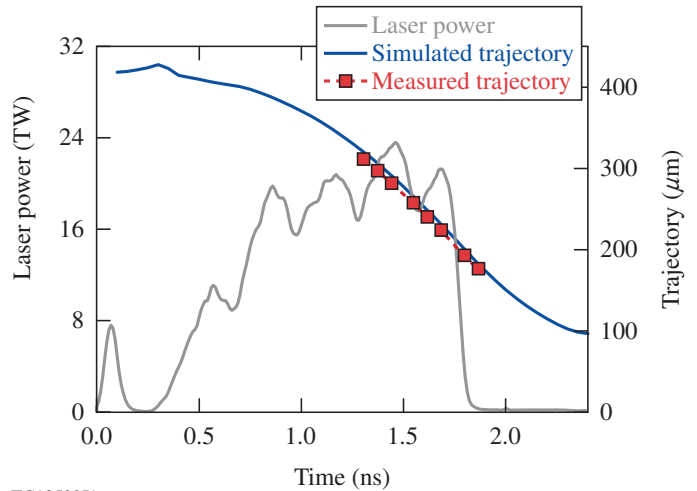


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FIG. 3: (color online). Simulated and measured corona temperatures at quarter-critical surface in corona plasma.

compares the measurement (by the channel H13B [29]) and the simulation of the time-resolved scattered-light power. The simulated power (blue line) shows very good agreement with the measured scattered-light power (dashed red line). The *LILAC*-simulated total laser absorption is 70% and the measured total laser absorption is 68%. Since the light refraction and frequency shift are sensitive to the corona spatial structure, the simulated coronal structure can be validated using time-dependent scattered-light spectral measurements. The simulated spectra [Fig. 2(c)] reproduce reasonably well the basic structure of the measured spectra [Fig. 2(b)] by H13B. However, at the rising phase of the compression main pulse ( $\sim 0.5$  ns), less simulated blue shift is obtained when compared with the measurement, which is attributed to the slower corona plasma expansion in the simulation.

Hot-electron production is an important issue for implosion performance, especially for low-adiabat ( $\alpha$ ) cryogenic implosions [6], where fuel preheating degrades the hot-spot pressure as  $P_s \sim \alpha^{-0.9}$ , and the shell areal density as  $\rho R \sim \alpha^{-0.54}$  [30]. Hot electrons can be generated by the nonlinear processes of laser-plasma interactions, including the three-wave parametric instabilities: stimulated Raman scattering (SRS), two-plasma decay (TPD) and filamentation instability, when the laser intensity is  $5 \times 10^{14} \sim 2 \times 10^{15}$  W/cm<sup>2</sup> for conventional direct- and indirect-drive ICF [31, 32]. In OMEGA direct-drive implosions, the coincidence of TPD signatures, combined with the absence of SRS-backscattered light, is considered evidence for the dominance of the TPD instability over other potential sources of hot electrons or harmonic emission. The half-integer harmonic spectra measured by the full-aperture backscatter stations (FABS) can be used to investigate the TPD instability, and the corona temperature at the quarter-critical surface can be inferred by the wavelength shift [32, 33]. As shown in Fig. 3, the



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FIG. 4: (color online). Simulated and measured shell-ablation-surface trajectories and the laser power pulse.

measured corona temperatures at the quarter-critical surface with two different channels (FABS30 and H10) are in very good agreement with the *LILAC* simulation. As a result, the time-dependent corona plasma conditions, including the expanding and inward movements, can be reasonably modeled by 1D *LILAC* simulations with non-local and CBET models.

A time-resolved, four-channel hard x-ray detector (HXRD) [34] provides a measurement of the time history of the hard x-ray emission and hot-electron temperature. In our experiment, the hot-electron temperature was measured to be  $\sim 50$  keV. A simple formula, balancing Bremsstrahlung emission and stopping power for energetic electrons, is used to relate the Bremsstrahlung emission  $E_{Br}$  (total time-integrated spectral emission) to the amount of energetic electrons [35]:

$$E_{Br} \left( \frac{\text{KeV}}{\text{KeV sr}} \right) = \frac{6.3}{4\pi} \times 10^9 \langle Z \rangle E_{hot} (J) e^{1 - \frac{h\nu}{T_{hot}}} \quad (2)$$

where  $\langle Z \rangle$  is the effective atom number,  $E_{hot}$  is the hot electron energy, and  $T_{hot}$  is the hot-electron temperature. The measured hard x-ray energy is  $\sim 22.3$  mJ, with Eq. (2) the conversion efficiency ( $E_x/E_{hot}$ ) from hot-electron energy to hard x-ray can be obtained as  $\sim 0.00061$ , and the absorbed-laser-to-hot-electron conversion efficiency ( $E_{hot}/E_a$ ) is  $\sim 0.21\%$ , where  $E_a$  is the absorbed laser energy. Because of the low  $E_{hot}/E_a$ , the preheating caused by hot electrons is not the dominant performance-degradation mechanism in our experiment.

In the experiment, the soft x-ray emission from a warm plastic target was measured with an x-ray framing camera (XRFC) and used to determine the shell trajectory [36]. The submicron-level accuracy of this method results from using emissivity profile features that do not require Abel inversion to analyze and are insensitive to perturbations of the ablation front [37]. The comparison of the measured shell trajectories with simulations

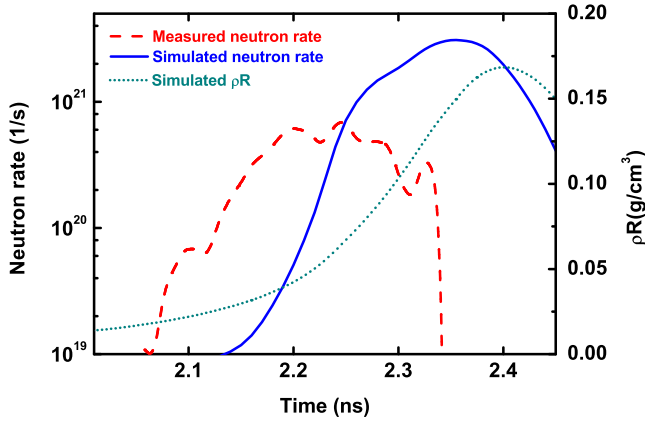


FIG. 5: (color online). Comparison of measured neutron rate, *LILAC* predicted neutron rate, and predicted evolution.

postprocessed to account for the time integration, the spatial resolution and the filtering of the diagnostic [38] are shown in Fig. 4, and good agreement is obtained, which implies the acceleration phase in the experiment can be reasonably modeled in the *LILAC* simulation with the nonlocal and CBET model, and the ablation-surface trajectory is independent on the shell perturbation.

The neutron temporal diagnostic (NTD) was used to measure the neutron rate’s history [39]. Figure 5 shows the simulated and measured neutron rates along with the simulated evolution. It also shows that the increases during neutron production and the fusion reactions are quenched near the time the areal density reaches  $0.12 \text{ g/cm}^2$ . The measured neutron rate is lower and truncated compared to the 1D-simulated fusion rate, likely because of the shell mixing [40]. The shell’s outside-surface instabilities grow at the acceleration phase, feed through the shell to its inner surface, and interact with the initial inner-surface perturbations. The shell’s inner-surface instabilities grow during the deceleration phase, leading to mixing into the hot spot. The perturbation could degrade the implosion performance, increase the hot-spot size, and decrease the hot-spot pressure and temperature at stagnation [28]. The nuclear reactions could occur earlier compared to the 1D clean implosion because of the compression of the spikes. Therefore, an earlier bang-time can be achieved with a lower neutron rate compared to the 1D simulation. These issues are clearly demonstrated in Fig. 5. However, there could be other reasons for the earlier bang-time in the experiment, like a higher velocity or a less back pressure at stagnation, and also the ablator may be burned through and lead to unknown confinement at stagnation. 2D/3D simulation is needed to investigate the hot-spot and shell dynamics at the deceleration and stagnation phases.

### III. PROPERTIES OF HOT-SPOT EMISSION IN A WARM PLASTIC-SHELL IMPLOSION ON OMEGA

An analytical model (thin-shell model) [41] was used to investigate the deceleration phase of the warm plastic-shell implosion on OMEGA. This model was derived by solving the conservation equations for the hot spot. The heat flux and the radiation energy leaving the hot spot go back in the form of inertial energy and  $pdV$  work of the material ablated off the inner shell surface. Although the hot-spot temperature is reduced by the losses due to heat conduction, the hot-spot density increases because of the ablated material entering the hot spot in such a way that the hot-spot pressure is approximately independent of heat conduction [41]. Consequently, heat conduction and radiation transport are ignored in the model. A formula for the shell trajectory can be obtained in a straightforward manner by this thin-shell model:

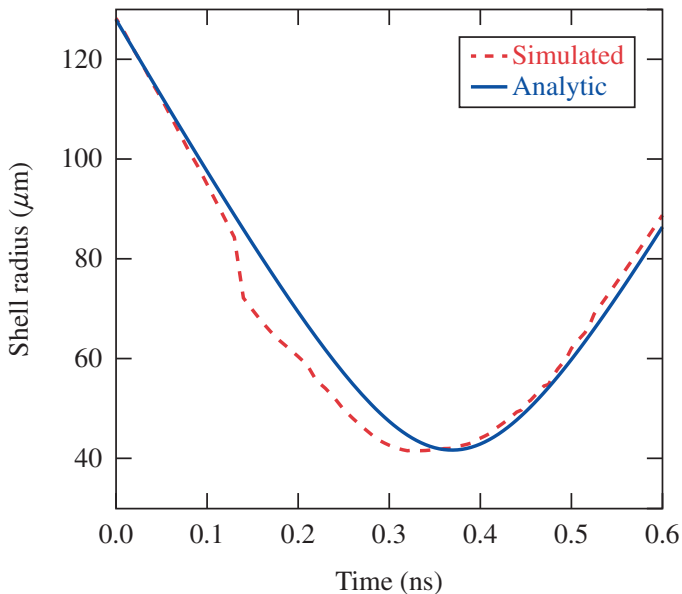
$$\hat{R} = \sqrt{1 - 2\hat{t}\hat{U}_0 + \hat{t}^2(1 + \hat{U}_0^2)} \quad (3)$$

where  $\hat{R}$  is the shell radius normalized to the initial shell radius  $R_0$  at the start of the deceleration phase,  $\hat{t}$  is the time normalized to  $\tau_0$  with the expression  $\tau_0 = \left[ \frac{M_{shell}}{4\pi P_0 R_0} \right]^{0.5}$ , where  $M_{shell}$  and  $P_0$  are the initial shell mass and hot-spot pressure at the start of the deceleration phase.  $\hat{U}_0$  is described as  $\hat{U}_0 = U_0\tau_0/R_0$ .  $U_0$  is the average shell implosion velocity at the beginning of the deceleration phase. In our warm plastic-shell implosion,  $R_0 \sim 128 \text{ }\mu\text{m}$ ,  $P_0 \sim 0.13 \text{ Gbar}$ ,  $U_0 \sim 300 \text{ }\mu\text{m/ns}$ , and  $M_{shell} \sim 0.03 \text{ mg}$ , leading to  $\tau_0 = 1.2 \text{ ns}$  and  $\hat{U}_0 = 2.9$ .

Figure 6 shows the evolutions of the shell radius (shell mass center) in our implosion according to both the *LILAC* simulation and the thin-shell model [Eq. (3)] without alpha heating. Since  $\text{D}_2$  gas was used in the target, the no-alpha-heating hypothesis is quite reasonable. As shown in Fig. 6, very good agreement was obtained in the first 0.1 ns. However, at about 0.12 ns, there is an inward jump of the shell radius, because the rebound shock collided with the inward-moving shell, leading to a sudden density increase near the shell’s inner surface. The “rebound-shock shell collision” is seen distinctly in the *LILAC* simulation, and is not seen in the analytical thin-shell model. This results in an earlier stagnation time, but the stagnation hot-spot radius is not sensitive to the “rebound-shock shell collision”.

*Spect3D* was used to simulate the target emission from the implosion. Since the KBFramED [42] is always used to investigate the hot-spot evolution in experiments, the effect of the KBFramED response should be considered within the *Spect3D* simulation. The spectral response of the KBFramED x-ray camera is shown in Fig. 7(b). The response function is nearly Gaussian in shape with spectral widths of  $\sim 1 \text{ keV}$  centered at energies near  $\sim 5.5 \text{ keV}$  [13].

The *Spect3D*-simulated hot-spot radius with KBFramED response is shown in Fig. 7(a), and



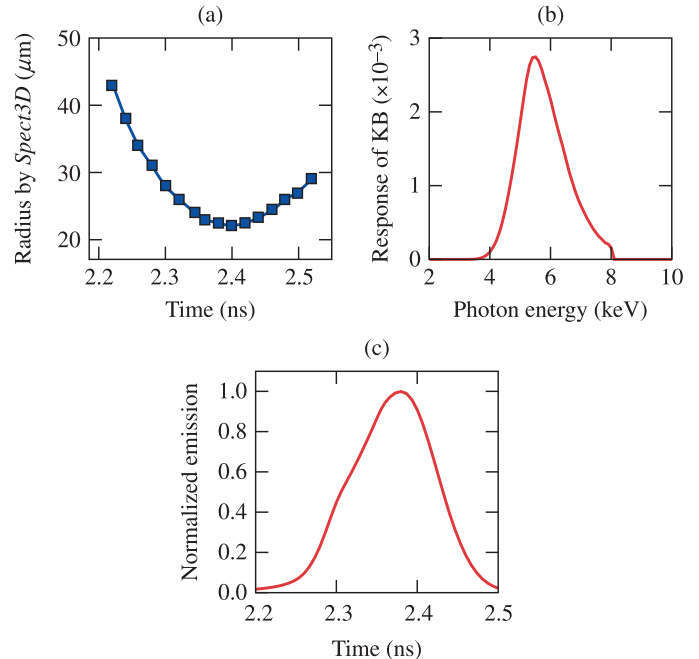
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FIG. 6: (color online). Evolutions of the shell radius by *LILAC* simulation and thin-shell model without alpha heating. The start of the deceleration phase (the end of the laser pulse) is 0 ns.

the hot-spot radius was chosen to be the 50% fall off location. During the deceleration phase, the hot spot is formed, and the temperature and density in the hot-spot region keep increasing until stagnation. In our *Spect3D* implosion simulation, the radius indicated by hot-spot emission is measurable with a radius of  $45 \mu\text{m}$  at  $\sim 2.2$  ns, and the hot-spot radius converges to  $22.5 \mu\text{m}$  at 2.4 ns (stagnation occurs). After stagnation, the target expands and the hot-spot radius increases. As a result, a “U”-shaped hot-spot radius evolution is formed.

The normalized total x-ray emission (spectrum- and space-integrated) evolution with the KBFramED response is shown in Fig. 7(c). As can be seen, the hot-spot emission intensity is nearly Gaussian in shape with the peak at stagnation, although the smallest core size is at stagnation.

The normalized density and  $T_e$  profiles by *LILAC* simulation at stagnation are shown in Fig. 8. The radiation and thermal flux from the hot spot deposit energy at its inner surface, and create a step shape in the shell’s density profile.  $T_e$  falls from the target center to the hot-spot boundary. Figure 8 also shows the x-ray emissivity profiles by *Spect3D* and the analytical thin-shell model. As can be seen, the brightest x-ray emission is located at the hot-spot boundary, and this feature marks the hot-spot radius in Fig. 7(a). The x-ray emission keeps increasing from the hot-spot center to the hot-spot boundary, reaches a peak at the boundary, and then decreases abruptly because of the low temperature in the shell. The brightest emission intensity at the hot-spot boundary is  $1.7\times$  the target center’s emission intensity. In the thin-shell model with an isobaric hot spot, analytical derivations were given for  $T_e$  and density profiles in



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FIG. 7: (color online). (a) *Spect3D* simulated hot-spot radius with the KBFramED response (the photon energy is 4 to 8 keV). (b) The KBFramED response. (c) Time-dependent emission of the implosion filtered with the KBFramED response.

the hot spot as [41]:

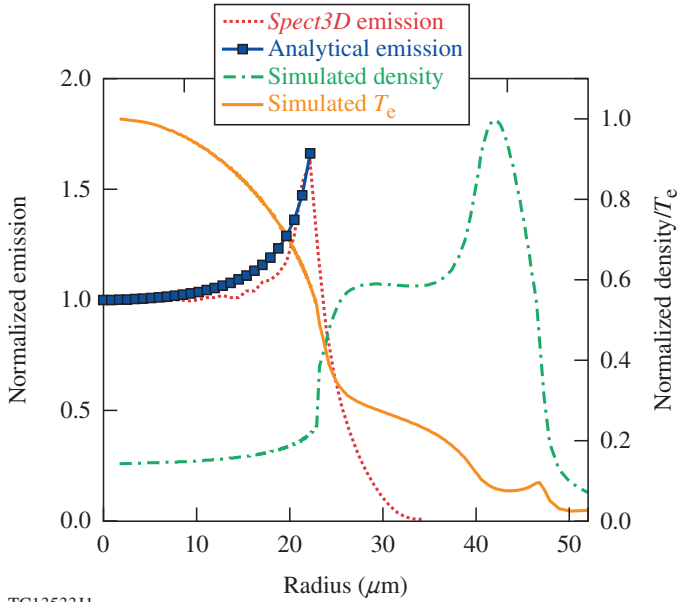
$$T(\hat{r}) = T_0 \frac{(1 - \hat{r}^2)^{0.4}}{1 - 0.15\hat{r}^2} \quad (4)$$

$$\rho(\hat{r}) = \rho_0 \frac{1 - 0.15\hat{r}^2}{(1 - \hat{r}^2)^{0.4} + \epsilon} \quad (5)$$

where  $T_0$  and  $\rho_0$  are the temperature and density in the hot-spot center,  $\hat{r}$  is the position normalized to the hot-spot radius, and  $\epsilon$  is an *ad hoc* term to remove the singularity at  $\hat{r} = 1$ . A commonly used hot-spot temperature profile  $T(\hat{r}) = T_0(1 - \hat{r}^2)$  [43] is in very good agreement when compared with Eq. (4). A simple expression for the Bremsstrahlung emissivity [44]:

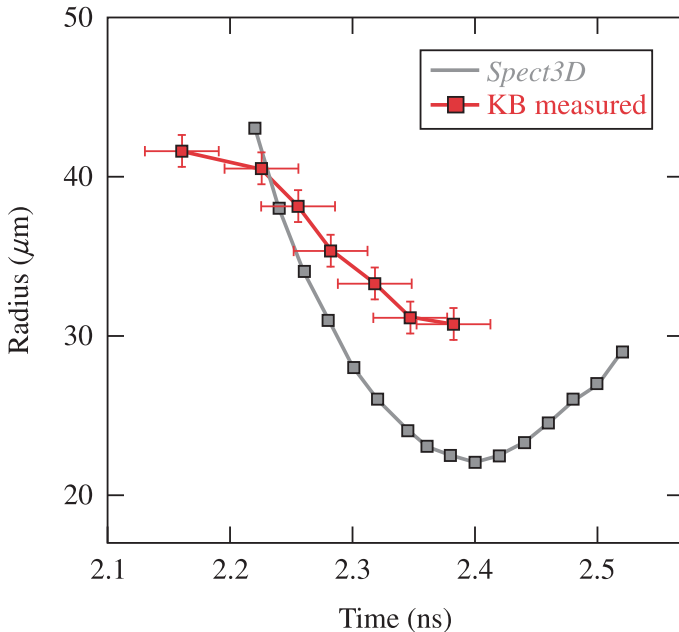
$$I \sim Z^3 n_e^2 T_e^{0.5} \quad (6)$$

is used here to investigate the hot spot’s x-ray emissivity profile. With the profiles from Eqs. (4) and (5), the calculation of normalized analytical x-ray emission shown in Fig. 8 is straightforward. Very good agreement is achieved between the *Spect3D* and analytical results, and it can be concluded that the hot-spot profiles given by the thin-shell model [Eqs. (4) and (5)] and the simple Bremsstrahlung emission formula [Eq. (6)] can be reasonably used to investigate the x-ray emission properties in our warm-plasma implosion.



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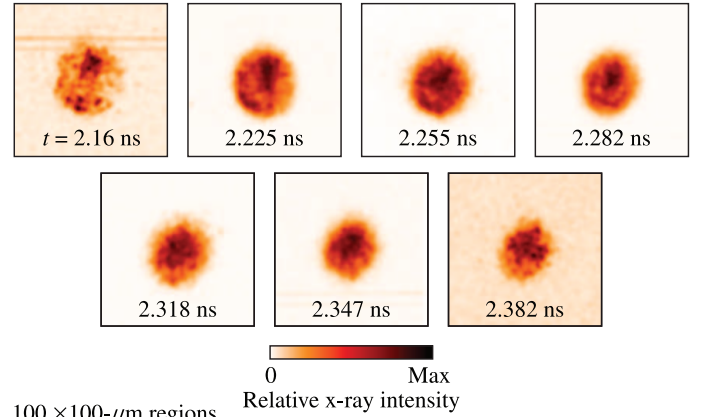
FIG. 8: (color online). Normalized profiles of hot-spot density and  $T_e$  by *LILAC*, x-ray emission by *Spect3D*, and x-ray emission by an analytical thin-shell model. All the plots are at stagnation.



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FIG. 9: (color online). *Spect3D*-simulated “U”-shaped hot-spot radius and KBFramed measured hot-spot radius (shot 84605).

In the experiment, the 16-channel KBFramed in the 4 to 8 keV photon energy range [42] was used to measure the hot spot x-ray emission evolution. The 17% intensity contour radius  $R_{17}$  of the gated x-ray image is related to the hot-spot radius [5, 42]. For the shot 84605, the gate time is  $\sim 30$  ps, and the spatial resolution is  $\sim 6$   $\mu\text{m}$ . A resolution grid was used to obtain the spatial resolu-



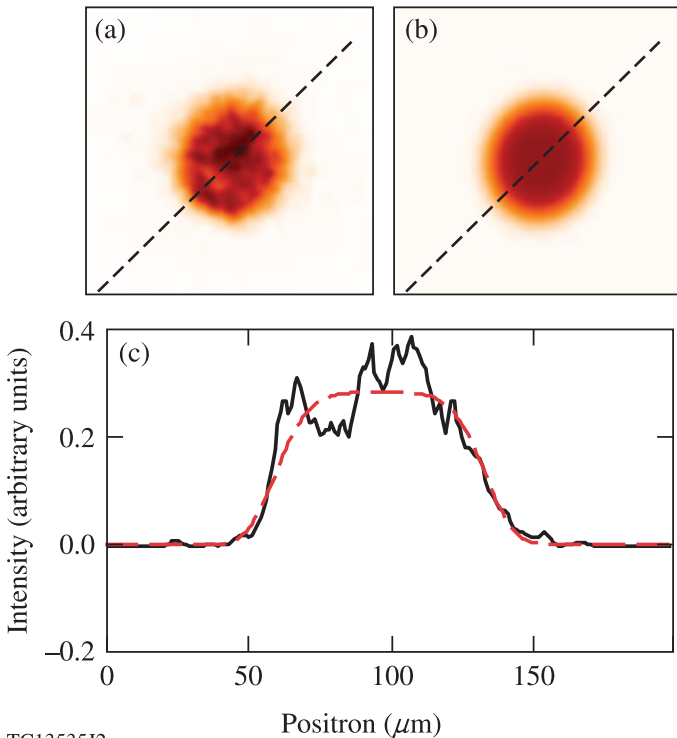
100  $\times$  100- $\mu\text{m}$  regions  
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FIG. 10: (color online). KBFramed images of hot-spot x-ray emission (shot 84605).

tion, a lineout through a single intensity-corrected image taken through the central 200- $\mu\text{m}$ -wide region, and the measured pattern was compared to the Gaussian-blurred step pattern whose FWHM is 6  $\mu\text{m}$  [42]. Spatially and temporally blurs have been performed over the detector resolution and gate width, and the KB spectral response [shown in Fig. 7(b)] has also been considered in the post-procedure of *Spect3D* simulation. In Fig. 7(a), it has been demonstrated that an “U”-shaped hot-spot radius evolution should be measured in a clean (or near clean) implosion by a KBFramed camera. In our experiment, however, the time-dependent hot-spot radius measured by a KBFramed is far away from the “U” shape. A fading away hot spot radius evolution was obtained as shown in Fig. 9. This significant discrepancy is a result of the hot-spot mixing caused by the unstable implosion. A larger hot-spot radius at stagnation was obtained compared to the 1D clean implosion. Figure 10 shows the images of stagnation (shot 84605) recorded by KBFramed with times so assigned from the beginning to the end of measurable core emission. Only 7 good signal level images were obtained since the emission was only present during an  $\sim 220$  ps time period. It should be noted that the structure could be caused by emissivity variation in space inside the hot spot or it could also be affected by absorption of the cold imploding D2 plasma surrounding the hot spot. However, the absorption is expected to be small at the average energy of the x rays that formed these images ( $\sim 4$  to 8 keV) for the range of areal densities expected ( $\sim 20$   $\text{mg}/\text{cm}^2$ ). Therefore, most of the structure should be caused by emission variation in the hot spot.

#### IV. A NON-ISOBARIC MODEL FOR HOT SPOT

To investigate the radial x-ray emission properties in the implosion, a two-dimensional (2D) super-Gaussian fitting was performed for the measured core images. The point-spread function (PSF) smoothed hot-spot image



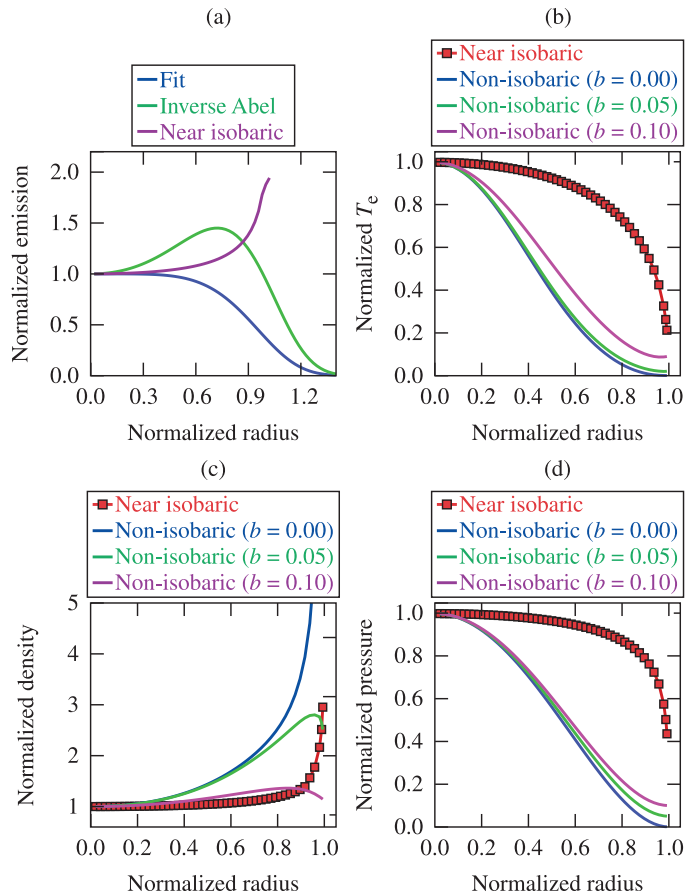
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FIG. 11: (color online). (a) The PSF smoothed image of the hot spot recorded at stagnation by the KBFramED (shot 84605). (b) The super-Gaussian fit of (a). (c) The measured and fitted intensity profiles taken through the centers of the x-ray images along the dashed lines in (a) and (b).

at stagnation is shown in Fig. 11(a), the corresponding super-Gaussian fit is demonstrated in Fig. 11(b), and the measured and fitted intensity profiles taken along the dashed lines through the center of the images are shown in Fig. 11(c) [5, 42].

The isobaric state of the hot spot at stagnation is widely used in ICF implosions [13, 41, 45]. The isobaric hot-spot condition and temperature density scaling of the neutron-production rate explain a scaling behavior of the x-ray yield as a constant power of the neutron yield [13, 14, 19]. In addition, the isobaric hot-spot profile at stagnation is used to derive the thin-shell model [41] and hydro scalings of the implosion performance [30]. Furthermore, the hot-spot pressure at stagnation is inferred from x-ray and nuclear diagnostics assuming an isobaric hot spot [5, 46]. Within the isobaric hot spot condition, the x-ray emissivity profile simulated by the thin-shell model had the brightest emission intensity at the hot-spot boundary, which has been proven by the *Spect3D* simulation (shown in Fig. 8). However, the experimental hot-spot emission does not peak at the hot-spot boundary (Fig. 11 and Ref. [5]).

A static model of the core was built to gain additional insight into target performance [47, 48]. This model assumed that the compressed core can be divided into two regions: a “clean” region with only fuel material and a “mixed region” in which some of the shell material is



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FIG. 12: (color online). The hot-spot x-ray emissivity profile by fitting, the emissivity profile after inverse Abel transform, and the emissivity profile by the isobaric thin-shell model. (b) The normalized  $T_e$  profiles by the thin-shell isobaric model, and non-isobaric model with different parameters. (c) The normalized density profiles by the thin-shell isobaric model, and non-isobaric model with different parameters. (d) The normalized pressure profiles by the thin-shell isobaric model, and non-isobaric model with different parameters. All the x axes are normalized to the hot-spot size  $38 \mu\text{m}$  at stagnation.

mixed with the fuel material. The experimental results (primary neutron burn rate, average neutron ion temperature, secondary neutron, proton, and knock-on yields) were compared to the data from the static model [47, 48].

It should be noted that the degree of uniformity of mixing in the hot spot is not well known at this time. There are several mechanisms for bringing ablator/fuel material into the hot spot, including various mode hydrodynamic instabilities at the ablation front and fuel-ablator interface, jets from capsule-surface defects, fill tube and target tent in indirect drive, and mounting stalk in direct drive [7, 33, 49]. Therefore, no one can determine exactly when and how mixing will occur, where mixing will be located, and for how long the mixing will evolve in the implosion. In this work, a hypothesis is proposed that the shell/fuel material mixes into the entire hot-spot area and no “clean region” exists. The new hot-spot model does not assume an isobaric pressure in the hot-spot region.

The hot-spot density and temperature deviate from the thin-shell model predictions because of mixing, although the thin-shell model has been demonstrated to get good agreement with the *LILAC* and *Spect3D* simulations in Figs. 6 and 8. In this new model, it is assumed that the mix is uniformly distributed in order to allow an average atomic mix fraction of CH to D<sub>2</sub>; however, the calculation is valid to a good degree even if the CH is strongly localized, provided that the pressure and temperature equilibrium conditions are maintained in the hot-spot volume [14, 48]. We used this model to investigate the hot-spot temperature, density, and pressure profiles, corresponding to the measured hot-spot x-ray emissivity profile, and we call this the “non-isobaric” model.

In a 1D implosion the hot spot is hot enough that the sound speed exceeds the radial flow velocity. This leads to a subsonic hot spot ( $Mach^2 \sim V^2/t < 1$ ). Under these conditions, the hot spot is isobaric as shown by scaling each term in the momentum equation  $\rho(\partial_t + V\partial_r)V = -\partial_r P$ . Since the time scale  $t \sim R/V$ , and  $\partial_r \sim 1/R$  (where  $R$  is the hot-spot radius), then the left hand side is of order  $Mach^2$  with respect to the right hand side and it can be neglected leading to  $\partial_r P \sim 0$  and  $P$  is constant (isobaric). In the presence of mix propagating from the hot spot boundary towards the center, the temperature in the mixed region becomes low enough that the Mach number ( $Mach^2 \sim V^2/t$ ) is of order unity and the left hand side of the above equation cannot be neglected and the hot spot pressure gradient is finite (non-isobaric hot spot). For example, using a linear profile of velocity  $V = V_{hs}r/R$  into the above equation leads to  $\rho(V'_{hs} + V_{hs}r/R)r/R = -\partial_r P$  resulting in a quadratic pressure profile for a constant density. In our 1D implosion, the implosion velocity is 234 km/s and the  $T_i$  is 2.8 keV, the Mach number  $V^2/T$  is about 0.1. If mix occurs, the hot spot boundary  $T_i$  decreases to 0.1 keV, then the Mach number changes to  $\sim 1$ . As a result, the non-isobaric implosion is introduced into this work.

The fitted hot-spot x-ray emissivity profile at stagnation is normalized and shown in Fig. 12(a). However, this emissivity profile was from the image plane. The radial hot-spot emissivity distribution was recovered from the inverse Abel transform of the imaged intensity [13] and is shown in Fig. 12(a). When compared to the emissivity profile by the analytical thin-shell model, the radial hot-spot emissivity profile has its highest intensity at  $\hat{r} = 0.7$ , as compared to a peak intensity at the hot-spot boundary in the thin-shell model (and also the *LILAC* and *Spect3D* simulations in Fig. 8). This significant discrepancy is caused by the mixing of the shell material (CH) into the hot-spot region.

Since the isobaric assumption cannot reproduce the measured hot-spot emissivity profile, in our “non-isobaric” model, in order to recover the measured radial hot-spot emissivity profile, the non-isobaric hot-spot pressure profile at stagnation is assumed to be:

$$P(\hat{r}) = P_{hs}[(1-b)(1-\hat{r}^2)^a + b] \quad (7)$$

where  $P_{hs}$  is the pressure at the target center, and  $a$  and  $b$  are two parameters. With this non-isobaric model, the pressure drops from the hot-spot center ( $\hat{r} = 0$ ) to the hot-spot boundary ( $\hat{r} = 1$ ), and the pressure at  $\hat{r} = 1$  is  $bP_{hs}$  with  $b = 1$  is the isobaric condition. With the above non-isobaric model and Bremsstrahlung emissivity formula [Eq. (6)], the hot-spot temperature and density profiles can be straightforward:

$$T_e(\hat{r}) \sim [(1-b)(1-\hat{r}^2)^a + b]^{4/3} I(\hat{r})^{-2/3} \quad (8)$$

$$\rho(\hat{r}) \sim [(1-b)(1-\hat{r}^2)^a + b]^{-1/3} I(\hat{r})^{2/3} \quad (9)$$

where  $I(\hat{r})$  is the measured hot-spot emissivity profile.

At a sufficiently high spectral energy, typically  $h\nu > 3$  keV for implosions on the 60-beam OMEGA laser system, the imploded cores are optically thin and the x-ray measurements are a direct measure of the emissivity, free of absorption and other transport effects [13]. Therefore, the hot-spot emissivity profile obtained by inverse Abel transform can be used directly in the non-isobaric model as  $I(\hat{r})$ . However, there are two parameters  $a$  and  $b$  in the non-isobaric model. Here, we use  $a = 2$  and  $b = 0, 0.05, 0.1$ . As has described above,  $b$  is the ratio of the hot-spot boundary pressure to the target-center pressure, and  $b \sim 1$  recovers the isobaric pressure [Eq. (7)]. The normalized hot-spot temperature, density, and pressure profiles are presented in Figs. 12(b), (c), and (d), respectively.

In the previous static model, in the mix region, the shell density decreases linearly from the edge of the mix region to the boundary of the clean region, and the temperature decreases linearly from the edge of the clean region to the edge of the mix region. In the clean region, a single temperature and density are assumed [47]. In the refined version of this static model, the density is chosen to be constant in the clean fuel region and to vary linearly in the mixed region, and a Gaussian profile is assumed for the temperature [48]. In our non-isobaric model, there is no clean region, the temperature and pressure decrease from the hot-spot center to the boundary, and the density increases from the hot-spot center to the boundary. However, the parameters  $a$  and  $b$  should be determined experimentally, more work should be performed to investigate the relationship of parameters  $a$  and  $b$  to the hot-spot absolute emission intensity, the spectrum distribution, and the neutron yield, etc. We will address these issues in future work.

## V. CONCLUSIONS

In this work, a warm plastic-shell implosion was performed on the OMEGA laser system. The corona plasma was reasonably simulated by the 1D *LILAC* simulation with nonlocal thermal conduction and CBET models. Good agreement has been achieved with the measured and simulated scattered-laser light spectra,  $T_e$  at quarter-critical surface in the corona, and the shell trajectory.

The thin-shell model was used to analyze the shell radius evolution in the deceleration phase, and is in very good agreement when compared with the *LILAC* simulation. The *Spect3D*-simulated and the thin-shell model calculated hot-spot x-ray emissivity profiles demonstrate that the peak emission intensity occurs at the boundary of the hot spot. The time-dependent hot-spot radius by *Spect3D* presents a “U”-shaped evolution in a 1D clean implosion when the KBFramED response is involved. However, a fading away hot-spot radius evolution was measured in OMEGA warm plastic-shell implosion, because the shell/fuel material mixing into the hot spot causes unstable implosions.

The isobaric hot-spot model is widely used in ICF to simulate the derivation of the thin-shell model and hydrodynamic implosion scalings, the relationship of the hot-spot Bremsstrahlung emission to the neutron yield, and the measurement of the hot-spot pressure. In this work, in order to recover the measured hot-spot emissivity profile at stagnation, a non-isobaric model is proposed, and the normalized hot-spot temperature, density, and pressure profiles are obtained within this non-isobaric model. However, more work is needed to validate this non-isobaric model, and in future 2D/3D simulations should be performed to investigate the hot-spot emission properties, and the effect to the hot-spot emission when the ablator material mixes into the hot spot. It is well known that the hot-spot is isobaric without mixing, and we would like to investigate the isobaric to non-isobaric evolution in 2D/3D simulations, and recover the measured hot-spot emission profiles in 2D/3D simulations, although 2D/3D simulations are very expensive. A more refined version of this non-isobaric model should be developed to include the relationship of the hot-spot conditions to the hot-spot emission intensity, the emission spectrum distribution, the neutron and charged-particle spectra,

and mixing conditions. Additional experiments with different ablators should be performed to study the measured hot-spot emission characteristics. The absolute hot-spot emission should be considered to observe the mixing ablator mass into the hot spot. However, the absolute x-ray emission depends on the calibration of the Kirkpatrick-Baez microscope, which is very difficult at present.

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