

Modeling high-compression, direct-drive, ICF experiments

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Abstract. The success of direct-drive-ignition target designs depends on two issues: the ability to maintain the main fuel entropy at a low level and the control of the nonuniformity growth during the implosion. Modelling the ICF experiments requires an accurate account for all sources of shell heating, including the shock heating, radiation and suprathermal electrons preheat, and small-scale perturbation growth. To increase calculation accuracy, a new heat-transport model has been developed and implemented in the 1-D hydrocode *LILAC*. This model includes both the effect of the resonance absorption and the nonlocal thermal transport. The OMEGA experiments designed with the help of the new model have achieved high-areal-density ($\rho R > 200 \text{ mg/cm}^2$) fuel assembly in the low-adiabat cryogenic shell implosions.

1. Introduction

In the inertial confinement fusion (ICF) approach to fusion, a spherical shell filled with the deuterium–tritium (DT) mixture is compressed to reach a temperature of 10 to 12 keV in the lower-density central core region to initiate a burn wave through the higher-density, colder main fuel surrounding the core [1]. For an efficient fuel burn, a high fuel areal density (ρR) must be achieved at the peak compression. As shown in Ref. [2], the areal density depends mainly on the fuel adiabat α (defined as a ratio of the shell pressure to the Fermi-degenerate pressure at the shell density) and laser energy E_{MJ} ,

$$\rho R = \frac{2.6}{\alpha^{0.54}} E_{\text{MJ}}^{1/3}. \quad (1)$$

This paper presents the results of modeling ignition-relevant, low-adiabat cryogenic implosions performed on OMEGA [3]. There are three main sources of the adiabat increase in a directly driven shell: shock heating, preheat due to the radiation and suprathermal electrons, and the short-scale nonuniformity growth. In the following sections we describe the first two sources in detail

2. Shock heating

The adiabat in direct-drive-ignition designs is controlled mainly by hydrodynamic waves, in particular by the shocks launched by fast-rising parts in the laser pulse. A simplest pulse consists of: a lower-intensity foot that launches a shock wave (SW) into the fuel; the transition region during which a compression wave (CW) is initiated; and the main higher-intensity part. Calculations show that to prevent an excessive increase in the fuel adiabat, the coalescence of the CW with either the SW or a rarefaction wave, produced after the SW breaks out of the shell, should occur within the 10% of the inner fuel mass. This condition constrains the allowable shock-breakout time to $\Delta t_s/t_s < 5\%$. The shock-breakout requirements constrain the modeling accuracy of the absorbed laser energy E_s during the shock propagation. For a constant-intensity foot pulse, the shock-propagation time is $t_s \sim \Delta_0^{3/2} E_s^{-1/2}$, where Δ_0 is the initial shell thickness. It can be shown that the same scaling is obtained when the shock is launched by a narrow picket (with energy E_p) at the beginning of the drive pulse (used in the adiabat-shaping designs [4]). Using $\Delta t_s/t_s < 5\%$ leads to $\Delta E_p/E_p < 10\%$. To meet such an accuracy goal, the laser-absorption modeling used in hydrocode simulations must be revised.

2.1 Laser absorption modeling

To increase accuracy in the laser-deposition calculations, two main effects must be included in calculations: resonance absorption and nonlocal thermal-heat transport. This section will consider such effects.

Because of a steep density gradient produced early in the pulse, resonance absorption is important during the shock transit. A simplified model for calculating the fraction f_A of the incident laser energy absorbed due to resonance effects was described in Ref. [5]. In evaluating the resonance fields, however, this model neglected the Bremsstrahlung absorption of the laser energy. Corrected for the absorption, the resonance fraction becomes $f_A = f_c (1 + 8/\phi^2)^{-1}$ where f_c is the fraction of the laser energy that reaches the turning point and ϕ is defined in Ref. [5]. Simulations show that this is in a good agreement with more rigorous calculations and experimental data presented in Ref. [6].

Bremsstrahlung absorption in the plasma corona is sensitive to the density and temperature profiles in the subcritical-density region. The hydrodynamic profiles, in turn, are determined by the thermal conduction near the critical density, where steep temperature gradients prohibit using the Spitzer thermal flux q_{sp} [7]. It is considered a common practice to replace q_{sp} by a fraction f of the free-stream limit, $q_{fs} = nTv_T$, in the regions where $q_{sp} > f q_{fs}$ (the flux-limited model [8]). Since the flux-limiter value f cannot be determined directly from the physics principles, its value, usually a constant in time, is determined by comparing the simulation results with the experimental observables. Remarkably, such a simple model is able to successfully explain a large number of experiments with simple pulse shapes. The results of the Fokker–Plank simulations [9] indicate, however, that the flux limiter must be time-dependent. Since it is highly unpractical to obtain the temporal shape of the flux limiter based only on the experimental data, a thermal-transport model must be developed for self-consistent flux calculations. Such a model was proposed in [9], where the simplified Boltzmann equation was solved using the Krook approximation. The main criticism of such a model with the energy-dependent collisional frequency $\nu_{ei}(v)$ is the lack of particle and energy conservation. To recover the conservation properties, the Krook approximation has been modified by renormalizing the local density and temperature used in evaluating the symmetric part of the electron distribution function f_0 . The Krook model has the solution [9]

$$f = f_0 - \int^x G(x', v) e^{\xi/y} d\xi, \quad G = \lambda_{ei} \left(\frac{\partial f_0}{\partial x} + \bar{E} \frac{\partial f_0}{\partial e} \right), \quad (2)$$

where $\xi(x') = \int_x^{x'} dx''/\lambda_{ei}$, $e = mv^2/2T$, $y = \cos\theta$, $\lambda_{ei} = v/\nu_{ei}$, and $\bar{E} = eE_x/T$ is the normalized electric field. The renormalized density n' and temperature T' are found by integrating Eq. (2), multiplied by 1 and $mv^2/2$, yielding $n = n' - R_1$ and $3nT/2 = 3n'T'/2 - R_2$, respectively. Since R_1 and R_2 depend on f_0 , the renormalized quantities can be found by iterations. In support of the renormalization

procedure, we observe that the solution of the Boltzmann equations in the classical limit of a small ratio of the electron mean-free path λ_{ei} to the temperature scale-length L_T also leads to a modification in the symmetric part f_{sym} [10]. Deviations from a Maxwellian distribution are due to the contribution from the electron–electron collisions.

Next, we compare the results obtained using the described nonlocal model with the simulations based on the flux-limited Spitzer conduction. Figure 1 shows the effective flux limiter (defined as a maximum ratio of the nonlocal heat flux to the free-stream value q_{fs} in the vicinity of maximum q_{sp}) as a function of time for an $\alpha = 2$ cryogenic implosion. This figure shows a higher value of the flux limiter during the picket, indicating a larger predicted laser absorption and stronger the SW, compared to calculations based on a constant flux-limiter model. Then, as the laser intensity relaxes after the picket, the flux limiter takes on a reduced value, leading to a weaker CW. If these effects are not properly modeled in a simulation, they lead to a significant areal-density reduction.

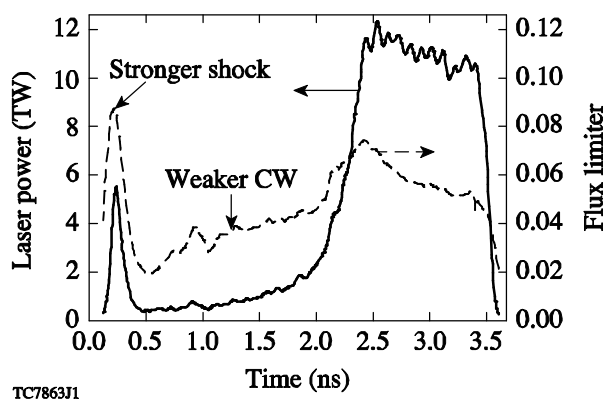


Figure 1. Laser power and effective flux limiter for $\alpha = 2$ cryogenic OMEGA design.

3. Suprathermal-electron preheat

As discussed in the Introduction, the degradation in ρR is significant if the adiabat at the inner part of the shell is increased. Electron preheat is important therefore if the deposition ranges exceed the shell ρR during the implosion. Thus, for OMEGA target designs, only electrons with energy in excess of 50 keV (90 keV for the NIF designs) can degrade the fuel assembly. The most important mechanism capable of producing such energetic electrons is the two-plasmon-decay instability [5]. The threshold [11] for this instability is $Th = I_{14}L_n(\mu\text{m})/230 T_{\text{keV}}$, where I_{14} is the laser intensity. The hot-electron preheat is quantified experimentally by hard-x-ray and $3/2\omega$ signal measurements. The above-threshold coefficient Th for a typical implosion of a shell with a $5\text{-}\mu\text{m}$ -thick CD overcoat over a $95\text{-}\mu\text{m}$ cryogenic layer is plotted in Fig. 2(a). The instability developed at the time when D_2 penetrates into the subcritical-density region. This explains the strong intensity dependence of the ρR reduction in such shells (for details see [12]). The enhanced absorption of materials with a higher-average ion charge Z suggested increasing the thickness of the CD overcoat layer to $10\ \mu\text{m}$, to prevent penetration of D_2 into the coronal region. Driven at $5 \times 10^{14}\ \text{W/cm}^2$ (the pulse shape is shown in Fig. 1), this design produced a significantly lower hard-x-ray signal, indicating lower suprathermal preheat. As a result, the areal density was very close to the predicted value. The areal density was inferred from the energy loss of the secondary protons while they propagate through the compressed fuel [13]. Both the simulated and measured spectrum, shown in Fig. 2(b), indicate the neutron-averaged value above $200\ \text{mg/cm}^2$ (see also [14]).

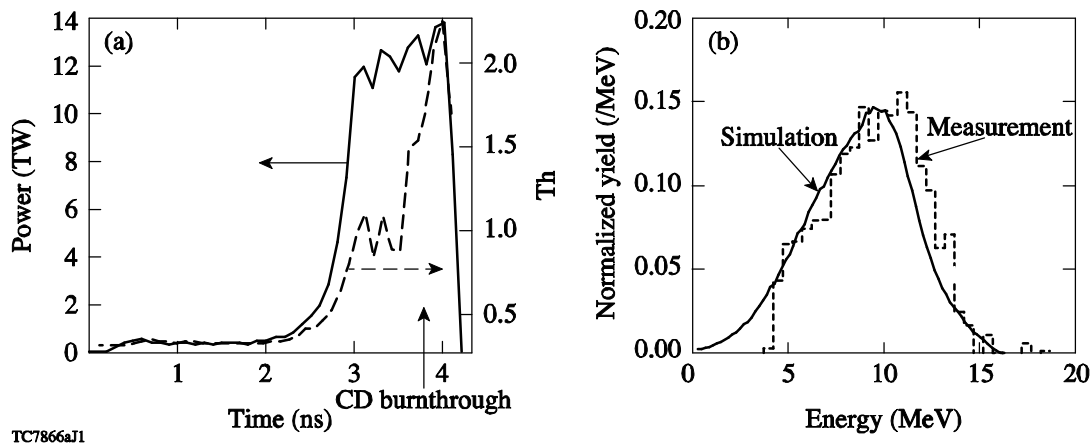


Figure 2. (a) Laser pulse and above-threshold parameter Th for 5- μm -thick CD overcoat, $\alpha = 2$ cryo design. (b) Charged-particle spectrum for 10- μm CD, $\alpha = 2$ cryogenic design presented in Fig. 1.

In conclusion, a new thermal-transport model was developed to improve the accuracy of the laser-energy-deposition modeling in ICF direct-drive implosions. The high areal density was experimentally achieved on the OMEGA system when the shock heating was optimized and suprathreshold-electron preheat was mitigated.

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