Implementing a Microphysics Model in Hydrodynamic Simulations to Study the Initial Plasma Formation in Dielectric Ablator Materials for Direct-Drive Implosions

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In direct-drive inertial confinement fusion (ICF), a spherical target is irradiated by laser beams to create the necessary conditions for fusion reactions. These targets contain the fusion fuel [deuterium (D) and tritium (T)] inside a plastic (CH) shell. The laser energy on the target causes the plastic to ablate outward like the exhaust of a rocket. This ablation creates a reaction force on the remaining part of the capsule. Ideally, one hopes that this should create a spherically symmetric implosion. However, single-beam speckle (laser imprint) can introduce perturbations that can compromise performance.[1] In fact, the laser energy deposited from a single-beam speckle penetrates through the target nonuniformly. This nonuniformity is intensified by the filamentation of the laser energy that leaves a damage track due to the self-focused laser radiation. These variations act as seeds to Rayleigh–Taylor instability, which grows exponentially. To create a uniform symmetric implosion for ignition, understanding and mitigating this laser-imprint process is important. As the laser beams irradiate the target, the target is ionized and a plasma is created around it. This coronal plasma determines the laser-energy deposition on the target until a critical surface is established and the target becomes opaque to the laser. After this, the subcritical underdense plasma absorbs the laser energy and transfers this energy through the electrons inside the critical surface to the ablation region.

Recently, it has been shown that the initial solid state of the target with specific electronic and optical properties has a notable impact on the subsequent plasma dynamics. It is important to implement a detailed model to understand the solid-to-plasma transition. Therefore, a microphysics model describing the response of the ablator material to the laser-irradiation process on the target has been developed.[2] The microphysics model incorporates a photoionization and impact ionization scheme that describes the transition of the solid ablator into plasma due to laser irradiation. Traditionally, hydrodynamic codes have ignored this detailed transition mechanism from the solid-to-plasma state for the target. The hydrodynamic codes either assume that the material is ionized to start with, and a critical electron density exists initially, or they adopt the "cold-start" method where the laser energy is deposited on the surface of the target to generate a critical surface in an *ad hoc* manner. Both of these strategies are incorrect from a physics perspective. Since radiation-hydrodynamic simulations form an essential component of our understanding of the direct-drive ICF process, it is important to incorporate the microphysics model into the hydrodynamic codes to model the seeds of Rayleigh–Taylor growth including the initial solid state of the target.

In this project, a revised version of the above-mentioned microphysics model[2] has been implemented into the 1-D hydrodynamic code *LILAC*. We demonstrate the implications of the microphysics model in ICF through hydrodynamic simulations for both spherical and planar targets. Unlike the *ad hoc* model, the microphysics model shows laser-energy absorption inside the target over time. Additionally, the energy absorption causes the electron temperature inside the target to rise; subsequently, the pressure inside the target increases. This is consistent with previous observations that the laser beam penetrates through the plastic and deposits energy inside the target since plastic on the outermost layer of the target is transparent to UV laser light of 351-nm wavelength.[3] This phenomenon had not been captured in previous hydrodynamic simulations since the incident laser intensity was restricted to the target surface by creating a critical surface in an *ad hoc* fashion.

This work focuses mainly on plastic or polystyrene ablators since they are commonly used ablator materials for direct-drive ICF targets. CH is a dielectric material with a band gap of 4.05 eV. This makes solid plastic transparent to UV laser light of 351-nm wavelength (or 3.53 eV), the wavelength of TW facilities like OMEGA. Therefore, the laser energy shines through the target in the early stage of laser irradiation. At present, hydrodynamic codes ignore the transparency of plastic to UV light, which is incorrect. To overcome these inaccuracies and develop a physics-based model, a rate equation governing the free-electron density of the electrons in the conduction band has been derived recently.[2] This rate equation as shown in Fig. 1(a) is coupled with a laser-energy–deposition scheme. Based on the laser-energy deposition, the plasma profile and the various physical quantities are determined. This model governs the dynamics of the initial plasma formation from the solid throughout the target during the early stage of the irradiation, until a critical surface is created. During this stage, the laser-energy deposition is mediated by the joule heating mechanism of the electrons in the corona. Once the critical surface forms, the material is ionized and assumed to be in the plasma state. After this time, the microphysics model dominates the plasma profile ahead of the shock front, while the normal *LILAC* method for inverse bremsstrahlung absorption dominates the physics behind the shock front as demonstrated in Fig. 1(b).

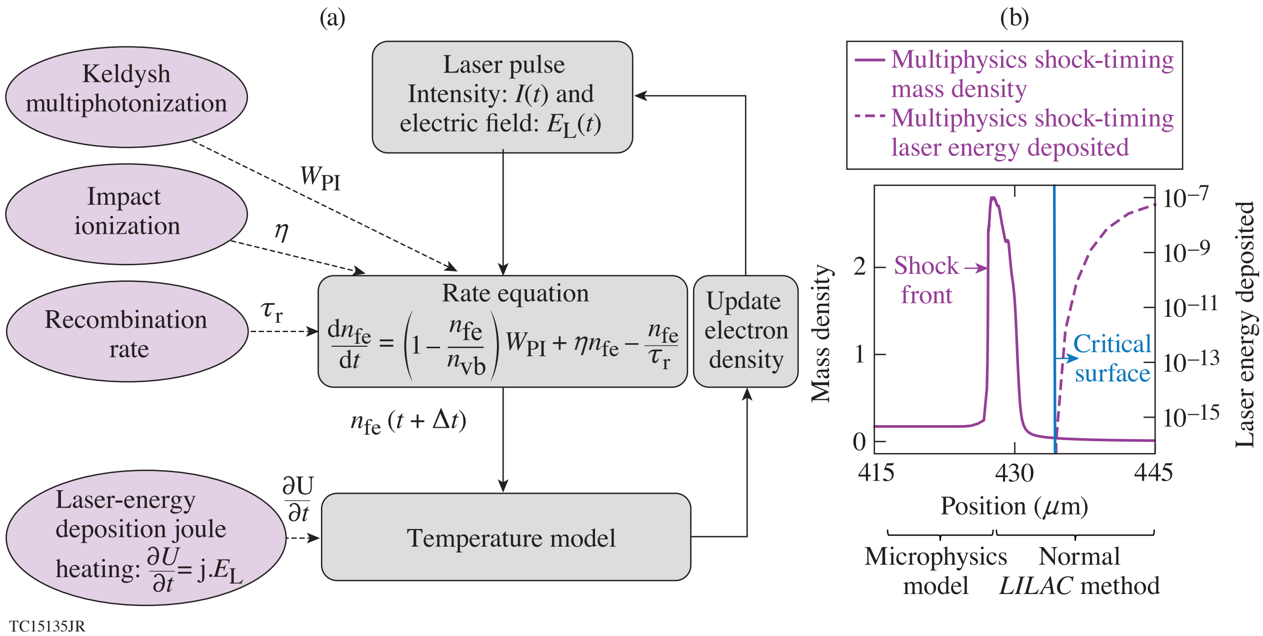

Figure 1
(a) A flowchart with detailed equations, different physical processes, and their implementation sequence inside *LILAC*. (b) An outline of the regions where the microphysics model and the normal *LILAC* method are implemented after the critical surface is formed.

After we implemented this microphysics model into *LILAC*, we examined how it affects hydrodynamic simulations in ICF. The effect of irradiating a solid plastic sphere [Fig. 2(a)] with a picket pulse [Fig. 2(b)] is discussed here. The solid CH sphere is initially transparent to the UV light before the critical surface formation occurs around 81 ps according to simulation. The microphysics model dominates the plasma profile for the entire sphere until the critical surface forms. Beyond that, the microphysics model controls the plasma profile ahead of the shock front. Figure 2(d) shows the plasma profiles in the radially outward direction, 300 μm from the center of the sphere. The plasma profiles are plotted at 75 ps, i.e., before the critical surface forms, at the peak of the picket pulse (200 ps) and at 400 ps, which is the end of the picket pulse. The microphysics model predicts a rise in the electron temperature and pressure before the shock wave travels through the target due to the shinethrough mechanism of the laser light inside the CH.

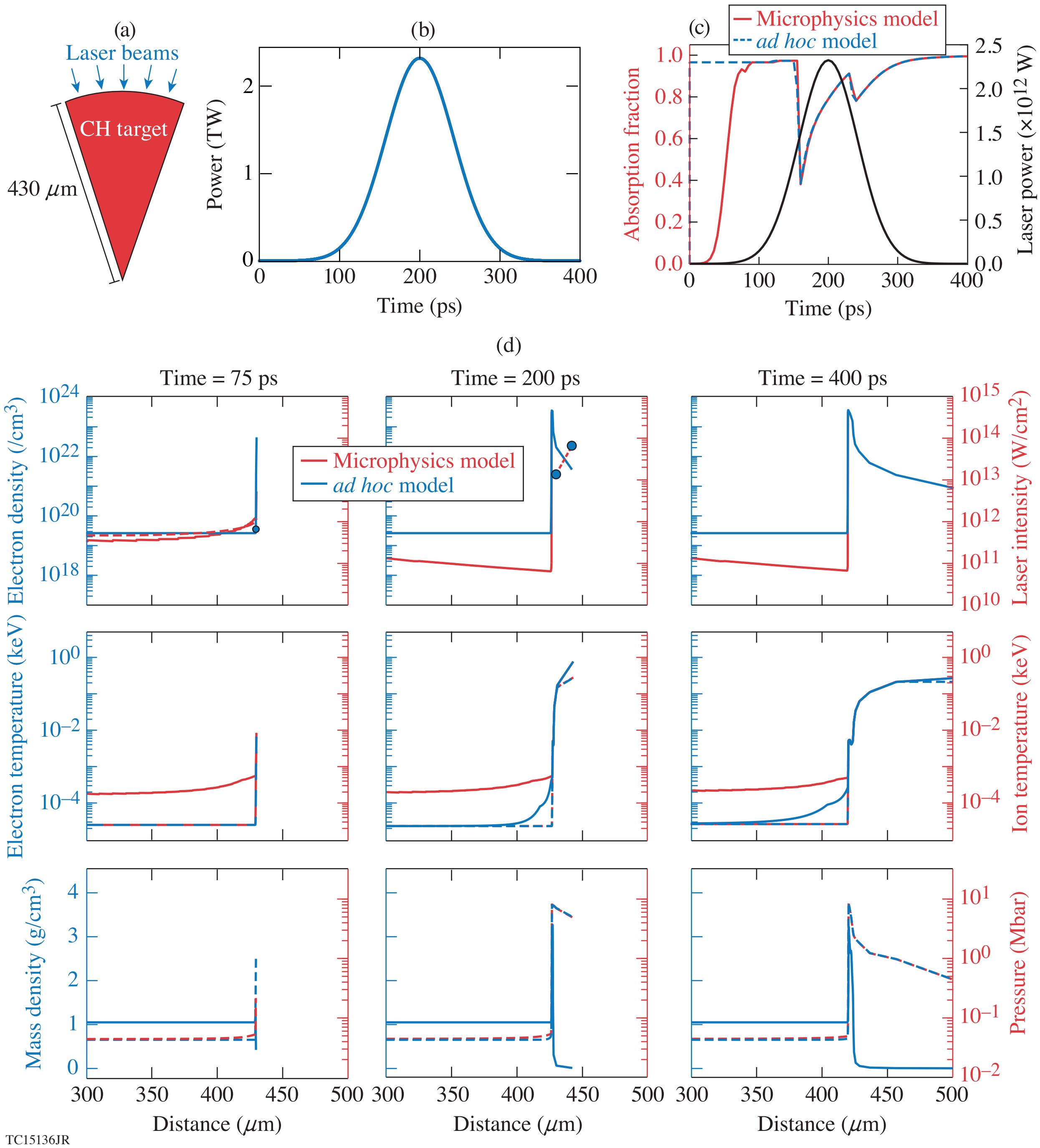

Figure 2
(a) A solid plastic sphere of 430-μm radius is irradiated with (b) a laser pulse of 250 J of energy; (c) the fraction of the incident laser energy absorbed over time. The absorption fraction between the microphysics model and the *ad hoc* model is initially different since the energy deposition is initially restricted to the surface of the target for the *ad hoc* model. Beyond the critical surface formation, the absorption profiles are the same since the plasma profile in the ablation region is controlled by the *ad hoc* model. (d) The plasma profiles from the microphysics model and the *ad hoc* model are plotted in red and blue, respectively. The top row shows the laser intensity deposition profiles (dashed red lines for the microphysics model and solid blue circles for the *ad hoc* model) and the corresponding free-electron density (solid lines). The critical surface formation occurs when the free-electron density rises to 9×10^{21} cm^{-3} for UV light. The middle row shows the rise in the electron temperature (solid lines) predicted by the microphysics model and the ion temperatures (dashed lines). The mass density profile (solid lines) and the difference in the pressure profiles (dashed lines) is evident in the lower row.

The next step is to implement the microphysics model into the 2-D hydrodynamic code *DRACO* for laser-imprint simulations. Perturbations to the ablation pressure as a function of angle due to the target response to laser imprint will be modeled with *DRACO*. Efforts to study the consequences of the microphysics model for a cryogenic implosion are also underway as the material properties of DT gas and DT ice are being investigated. It is necessary to know the band gap, collisional frequency, and recombination rates for these materials to accurately implement the microphysics model.

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