Energy Deposition Models for Short-Pulse Laser-Solid Interaction Experiments

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Abstract. Reliable models for the transport and deposition of energy in solid targets during short-pulse laser matter interactions are vital for designing and interpreting material properties experiments, and of clear relevance to the fast igniter. We conduct hybrid plasma simulations using LSP, considering relatively modest intensities to facilitate comparisons with radiation hydrodynamic models. The relative effects of thermal wave heating, direct collisional heating by fast electrons and Ohmic heating are discussed. Target heating depends strongly on the form of the hot electron distribution produced by the absorption of the incident laser pulse at the vacuum-matter interface. Where the hot electron population is assumed to be a discrete beam, we find good agreement with our models. For the case of a thermalised hot electron population, target heating by hot electrons is reduced. Under these conditions, the interplay between fast-electron and thermal wave heating is unclear, which has implications for target heating experiments.

1. Introduction
Recent results from target heating experiments have been successfully explained [1] by a combination of thermal wave heating and hot electron pre-heat. These experiments were conducted at intensities of the order of $10^{18}$Wcm$^{-2}$ using CH targets containing buried metallic layers. Radiation-hydrodynamic models [2] developed for modeling long pulse laser-plasma interactions have been applied in the short pulse regime and are in general agreement with experimental results. However, these models require a number of assumptions to be made and do not include physical effects known to be important in short-pulse laser matter interaction [3,4]. Furthermore, there are aspects of the physical model that merit further consideration, such as the origin of the thermal wave.

Here we briefly discuss the hydrodynamic model, including the treatment of fast electrons. This is followed by a simple, treatment of field-inhibited fast electron transport and comparison with results from the hybrid PIC code LSP [5]. These results aid the interpretation of radiation-hydrodynamic simulations and experimental results, offering some insight into the origin of the thermal wave.

2. Radiation hydrodynamic models
If we assume a fraction of the incident energy is absorbed into a thermal wave at the target surface, the target heating can be modeled using the radiation hydrodynamics code NYM [2]. Due to the non-linear conductivity the heat wave will be steep fronted in temperature and the heat flux, $Q$, into the target will be given by $Q = \kappa_\text{H} dT/dx \approx \kappa_\text{H} T/x$. Assuming the heat front penetrates supersonically to a
depth \( x \), then \( Q = \rho c_v x T / t \). Taking the thermal conductivity from Spitzer [6] gives a thermal penetration depth of \( x = 2.65 \times 10^{-4} (I_{\text{abs}})^{5/9} t^{7/9} \) cm, for CH at 1 g/cc where \( I_{\text{abs}} \) is the absorbed laser intensity.

This is confirmed with 1D simulations using a square-top 1 ps pulse incident on a 20 \( \mu \)m target. For these simulations, where the density scale length is short we assume a fixed absorption of 20\% of the incident energy. Figure 1 shows the temperature profile from NYM compared to the estimates given above. These results are potentially sensitive to the value of the flux limiter applied in the code. If the flux limiter used is low, it can influence the inward going heat front in a predictable way.

The main pulse in CPA laser systems is often preceded by a prepulse. Without the use of a plasma mirror, this is most significant on the HELEN laser system [7] when configured for red light. Simulations with realistic pre-pulse parameters demonstrate the formation of a hot corona in front of the target. The effect of this corona is to reduce the heat flux by an amount dependent on the flux limiter, but also to shock the dense material. The corona accounts for relatively little ablated mass, leading to negligible inverse bremsstrahlung. Other, collisionless, absorption mechanisms must be considered. These produce a population of hot electrons, often characterised by a temperature \( T_h \) [8, 9, 10]. We choose values for \( T_h \) consistent with published values; \( T_h = 85 \) keV and 180 keV, at \( I = 10^{18} \) W/cm\(^2\) for green and red light respectively. Hot electron cannot be included self-consistently in NYM. However, NYM does have a hot electron model, designed for modelling hot electron preheat in long pulse hohlraum experiments, based on a collisional deposition model [11]. The result is to preheat the target ahead of the thermal wave but the net effect on target heating is negligible. However, this model does not explain how the thermal wave is initialised and does not take into account the electric field inhibition of fast electron transport and associated effects.

![Figure 1. Thermal wave heating of a 20\( \mu \)m CH target by green light, after 1 ps as given by NYM (solid line) and estimated heating depth vs. temperature (dashed line).](image)

3. Simple Energy Deposition Models
Existing models [12] developed to model pre-heating of solid targets in long-pulse laser matter interaction can be adapted to account for field inhibited transport. Energy deposition of a hot electron distribution is characterised by a known stopping distance and a scaling between stopping distance and energy.

For collisionally dominated stopping, penetration depths of particles with a given energy are well known and scale with the square of energy. To adapt this model for electric field dominated stopping, consider the stopping distance, \( \lambda_h \) of an electron in a field \( E \) with energy \( \xi_h \) \( \lambda_h = \xi_h / E \). Scaling of penetration depth is therefore linear with \( T_h \). This scaling is used to estimate the rate of energy loss as an electron of a given initial energy moves into the target in the presence of the field generated by the total flux of hot electrons. Integrating over a given distribution of initial hot electron energies gives the energy deposition \( e(x) \) in J/g.
For a thermal distribution, with temperature $T_h$, where $I_{\text{abs}}$ is the intensity of absorbed radiation, $t$ is the pulse length and $L = x / \lambda_h$. Equation 2, as a function of $L$ is shown in Figure 2. Approximately 45% of the incident energy is deposited within the stopping range of an electron with energy $T_h$.

For a hot electron beam, centred at a beam velocity $v_b$, with a thermal velocity (in the beam rest frame) of $v_{tb}$

$$I(L) = \frac{1}{2} \sqrt{2} \left[ 1 + \frac{1}{2} \frac{v^2}{v_{tb}^2} \right] \left( 1 - \text{erf} \left( \frac{1}{v_{tb}^2} \sqrt{L - 1} \right) \right)$$

A simple temperature estimate for 10% absorption into hot electrons assumes perfect gas EOS at 100eV (for comparison with hybrid results). For the conditions under consideration ($I=10^{18}$, $T_h=85$keV (green) and $T_h=180$keV (red)), this predicts final temperatures of 540eV over 12μm and 199eV over 58μm.

For the case of a cold beam we calculate 296eV over 30μm for green light and 144eV over 130μm for red. Estimates can take into account the variation of the resistivity with temperature when estimating the range. In this case the final temperature has to be calculated iteratively. This ‘improved’ treatment gives over twice the range with a corresponding fall in temperature. The calculation with self-consistent resistivity agrees less well with simulations (see below). The reason for this is not clear but may be associated with enhanced inhibition due to the limited number of carriers (i.e. the ratio $n_{\text{hot}} / n_{\text{cold}}$).

![Figure 2. Energy deposition vs. depth into target $L=x / \lambda_h$](image)

Model assumes a linear scaling of penetration depth with energy and an initially Maxwellian distribution of energies.

4. Hybrid Model

We use the hybrid PIC code LSP [5] to model the transport of fast electrons in CH targets. This model includes physical effects absent from the hydro treatment. We consider a 2D CH target with 10% of the incident energy injected at the target edge with a temporal profile chosen to mimic the laser pulse. For the form of the injected hot electron distribution we adopt both beam and Maxwellian hot electron distributions. Beam results (see Figure 3) are in broad agreement with simple models. Results using a thermal distribution (see Figure 3) of hot electrons demonstrate a lower than expected heating at depth. The bulk of the hot electrons are trapped within a few microns at the target surface which heated to high temperatures. The energetic tail of the hot electron distribution moves through target with no significant transport inhibition. This may help explain the origin of the thermal wave in buried layer heating experiments, under conditions where absorption of a significant fraction of energy into a thermal wave at the surface is not expected.
5. Conclusions
Modelling target heating experiments at intensities of $I=10^{18}\text{Wcm}^{-2}$ and above presents a significant problem for hydro codes. Significant progress has been made in clarifying experimental results [1] but there is still some uncertainty about the nature of target heating. In particular, the application of existing hydro codes to the problem does not explain the origin of the thermal wave to which the heating is attributed.

Hybrid modelling with LSP offers considerable insight [13] into the potential importance of hot electron transport in these experiments and indicates that the rapid, field-induced, stopping of a significant fraction of the hot population may be responsible for depositing energy at the target surface and driving the thermal wave.

Simple estimates for target heating, based on pre-heat models for long-pulse interaction provide a reasonable agreement with hybrid simulations under certain conditions. These could potentially be used to augment the treatment of hot electron transport currently implemented in NYM.

There is still a degree of ambiguity over modelling such experiments which preclude the development of a predictive capability. Diagnosing the energy partition and absorption processes experimentally and determining the hot electron distribution via self-consistent numerical models are a clear priority for future work.

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