High Energy Density Physics 27 (2018) 12–17

Contents lists available at ScienceDirect

High Energy Density Physics

journal homepage: www.elsevier.com/locate/hedp

Laser ablation under different electron heat conduction models in inertial confinement fusion

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ARTICLE INFO

Keywords:
Electron heat conduction
Laser ablation
Inertial confinement fusion

ABSTRACT

In this paper, we study the influence of three different electron heat conduction models on the laser ablation of gold plane target. Different from previous studies, we concentrate on the plasma conditions, the conversion efficiency from laser into soft x rays and the scaling relation of mass ablation, which are relevant to hohlraum physics study in indirect drive inertial confinement fusion. We find that the simulated electron temperature in corona region is sensitive to the electron heat conduction models. For different electron heat conduction models, there are obvious differences in magnitude and spatial profile of electron temperature. For the flux limit model, the calculated conversion efficiency is sensitive to flux limiters. In the laser ablation of gold, most of the laser energies are converted into x rays. So the scaling relation of mass ablation rate is quite different from that of low Z materials.

1. Introduction

In indirect drive laser fusion, the intense laser power is absorbed in a high Z cavity (hohlraum) and converted into soft x rays. These x rays are used to produce an ablation drive that compresses a D–T fuel capsule placed at the center of hohlraum, driving it to ignition and burn [1,2]. In hohlraums, the laser energy is mainly absorbed by the corona plasmas, and transported into hohlraum wall by electrons. Electron transport is of great significance to hohlraum physics studies. It influences the hohlraum plasma conditions, the scaling relation of laser ablation and the conversion from laser into soft x rays.

In inertial confinement fusion (ICF) hohlraum studies, plasma conditions inside hohlraums are very important to laser energy deposition, radiation symmetry control, laser plasma interactions (LPI) and ignition hohlraum design [3–5]. Recent integrated experiments on the National Ignition Facility (NIF) [6,7] and the hohlraum experiments on the SGIII-prototype [8,9] indicate that radiation hydrodynamic codes cannot reproduce the experimental results well. As a result, the radiation hydrodynamic codes should be improved in order to precisely design the ignition experiments [7,10–14].

Most recently, two important physical models used in radiation hydrodynamic codes are reconsidered to understand the complicated hohlraum physics [15–17]. One is electron heat conduction model, and the other is non-local-thermodynamic-equilibrium (NLTE) atomic physics model. In order to precisely describe the electron transport in laser plasmas, many electron heat conduction models have been proposed and implemented in the radiation hydrodynamic codes [18,19,21,22]. However, the electron transport in laser plasmas is still an open question due to the complication of laser plasmas. In addition, there are few works studying the influence of electron transport models on the laser ablation of high-Z materials, such as gold (Au), which is typically used as the material of hohlraum wall. In this work, we will study the laser ablation of Au by using different electron heat conduction models, such as the flux limit model (FL model) [21], the nonlocal electron heat conduction (NL model) [23] and the electron heat conduction based on the non-Maxwellian distribution (NM model) [24,25]. For Au, the laser ablation is accompanied with the conversion from laser into soft x rays and the radiation ablation. In contrast, there is almost no conversion from laser into x rays in the laser ablation of low Z materials [26]. So, the laser ablation of Au is quite different from the laser ablation of low Z materials [2]. Here, we numerically study the influence of electron heat conduction models on the laser ablation of Au, and concentrate on the plasma conditions, the conversion efficiency from laser into x rays and the scaling relation of mass ablation. Our work may be helpful for understanding the hohlraum experiments in indirect drive ICF studies.

The paper is organized as follows. In Section 2, we give a brief introduction of the three different electron heat conduction models used in the simulation. In Section 3, the numerical results of laser ablation of plane Au target is presented firstly. Then, we compare the plasma conditions, the conversion efficiency from laser to x rays and the scaling relation of mass ablation obtained by using the different models, and

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https://doi.org/10.1016/j.hedp.2018.04.001
Received 11 October 2017; Received in revised form 14 March 2018; Accepted 18 April 2018
Available online 19 April 2018
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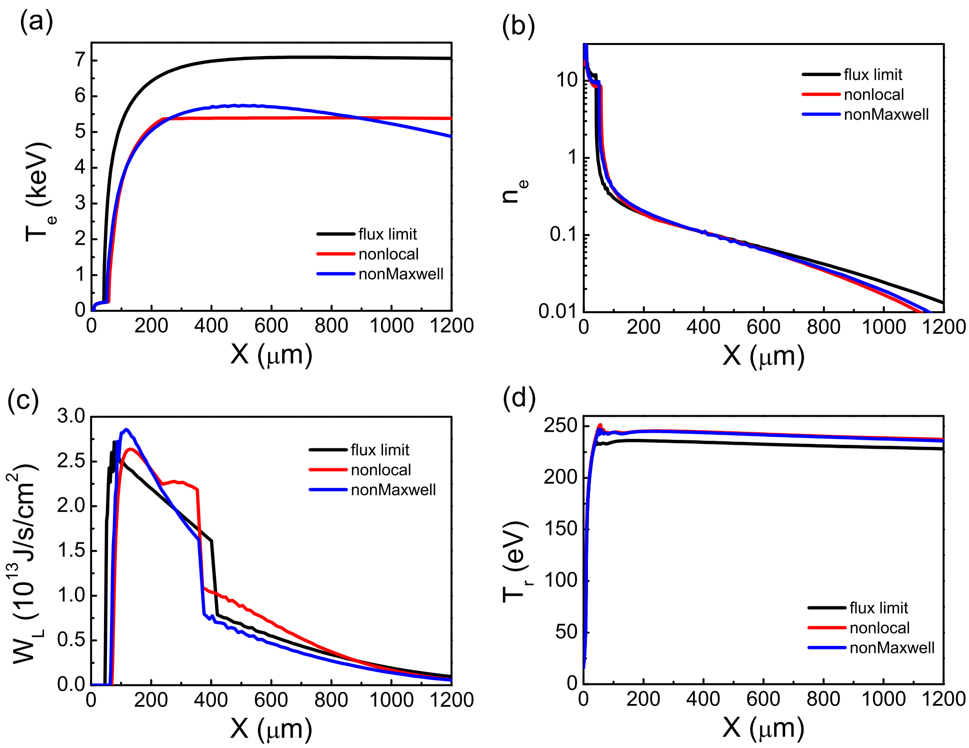

Fig. 1. The spatial distributions of electron temperature T_e (a), normalized electron density n_e (b), laser deposition W_L (c) and radiation temperature T_r (d) at 1.0 ns obtained by the different electron heat conduction models for laser ablation of the Au plane target. The black, red and blue lines correspond to the results of FL model, the NL model and the NM model, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

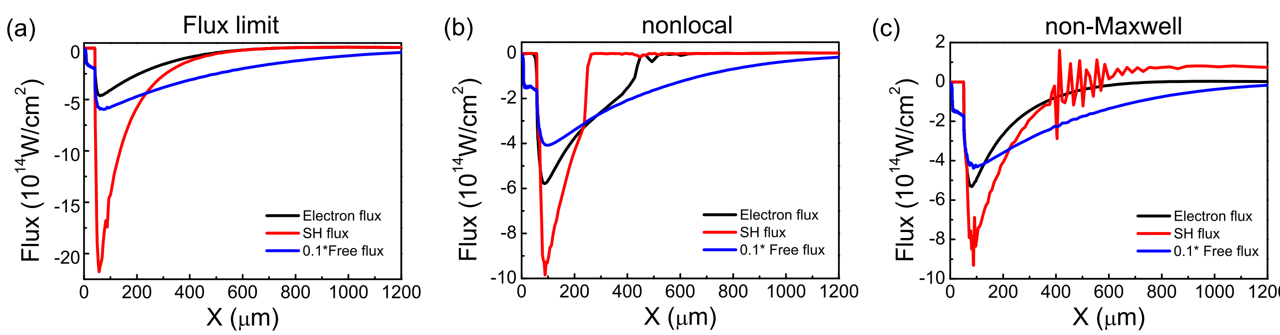

Fig. 2. The spatial distributions of electron heat flux at 1.0 ns obtained by the FL model (a), the NL model (b) and the NM model (c). The black, red and blue lines correspond to the electron heat flux used in the electron energy equation, the Spitzer–Härm heat flux and the 0.1 times of the free-streaming flux, respectively. The spikes in the SH flux are due to the numerical fluctuations. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

discuss the reasons for the differences. We will give a summary in Section 4.

2. Electron heat conduction models

In plasma physics, the electron transport theory was systematically investigated by Cohen et al. [18]. The explicit expression of electron heat flux in plasmas was derived by Spitzer and Härm [19]. In the Spitzer–Härm theory, the classical electron heat flux in an unmagnetized plasma is

$$q_{SH} = -\kappa\frac{\partial T_e}{\partial x}, \tag{1}$$

where κ is the electron heat conductivity,

$$\kappa = G(Z)\left(\frac{8}{\pi}\right)^{3/2}\frac{k_B(k_B T_e)^{5/2}}{m_e^{1/2}Ze^4\ln\Lambda}. \tag{2}$$

Here, T_e is the electron temperature, k_B is the Boltzmann constant, m_e is electron mass, Z is the average ion charge, e is the electron charge and $\ln\Lambda = \ln[(k_B T_e)^{1.5}/(\sqrt{4\pi N_e}e^3)]$ is the Coulomb logarithm [20]. N_e is the electron number density. $G(Z)$ is the factor accounting for electron-electron collisions in the electron transport.

In the Spitzer–Härm theory, the electrons with velocities about $4v_{te}$ contribute the most of heat flux, here $v_{te} = \sqrt{k_B T_e/m_e}$ is the thermal velocity. The Spitzer–Härm theory is valid for the plasmas in which the mean free path λ_4 of the electrons with thermal velocity is greatly less than the temperature gradient scale length λ_T, that is $\lambda_e < 0.02\lambda_T$ [28]. The electron mean free path λ is defined as

$$\lambda = \frac{m_e^2v^4}{4\pi N_e Ze^4\ln\Lambda}, \tag{3}$$

and the mean free path of electrons with thermal velocity is

$$\lambda_e = \frac{(k_B T_e)^2}{4\pi N_e Ze^4\ln\Lambda}. \tag{4}$$

The temperature gradient scale length λ_T is defined as

$$\lambda_T = \left|\frac{T_e}{\partial T_e/\partial x}\right|. \tag{5}$$

However, the temperature gradient is generally steep in laser produced plasmas due to the laser heating. And the electron mean free path may