A wide-range model for simulation of aluminum plasma produced by femtosecond laser pulses

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Abstract. We use a wide-range model of thermodynamic, transport and optical properties for simulation of laser-induced dynamics of aluminum plasma. The model describes the laser energy absorption, electron thermal conductivity and two-temperature effects of electron-ion collisions as well as hydrodynamic motion of matter. The model successfully describes experiments on self-reflectivity in wide range of intensities, and angular dependence of reflectivity coefficient for S- and P-polarized pulses. Thus, the model can be used for prediction of the main parameters of aluminum plasma such as temperature, density, velocity, mean charge of ions for optimization of planned experiments.

1. Introduction
Intense subpicosecond laser irradiation of metals engenders states out of thermal equilibrium between electron and ion subsystems. These non-equilibrium conditions were the subject of thorough study over the past decades. In contrast to the long nanosecond pulses [1, 2], ultrashort irradiation gives better resolution of physical processes involved in plasma dynamics. In particular, it has been investigated experimentally a self-reflectivity of aluminum targets irradiated by femtosecond laser pulses [3–5]. In addition, a more precise pump-probe technique has been applied to follow the dynamics of aluminum dense plasma within the subpicosecond time resolution [6, 7]. In this case the time evolution of the probe pulse reflectivity at short delays after the pump pulse demonstrated a fast change associated with the electron subsystem excitation. Besides, the phase shift data highlighted the plasma motion for longer delays after the pump pulse action. For accurate description of laser-irradiated target dynamics and optimization of experimental setups, it is necessary to use a self-consistent model joining models of optical, transport and thermodynamic properties of matter. In this paper, we present a wide-range model of aluminum that describes in the proper way the main parameters of the plasma produced by ultra-short laser pulses of different intensity, wavelength and angle of incidence.

2. Model
The particularities of the present model are described in our previous paper [8]. The model is based on 1D two-temperature hydrodynamic equations in Lagrangian form that describe
conservation of mass, momentum and energy of electron and ion subsystems:

\[
\frac{\partial (1/\rho)}{\partial t} - \frac{\partial u}{\partial m} = 0, \tag{1}
\]

\[
\frac{\partial u}{\partial t} + \frac{\partial (P_e + P_i)}{\partial m} = 0, \tag{2}
\]

\[
\frac{\partial e_e}{\partial t} + P_e \frac{\partial u}{\partial m} = -\gamma(T_e - T_i)/\rho + Q_L/\rho + \frac{\partial}{\partial m} \left( \kappa \rho \frac{\partial T_e}{\partial m} \right), \tag{3}
\]

\[
\frac{\partial e_i}{\partial t} + P_i \frac{\partial u}{\partial m} = \gamma(T_e - T_i)/\rho. \tag{4}
\]

Here \(\rho\) is the material density; \(m\) is the mass coordinate; \(t\) is the time; \(u\) is the velocity; \(P, e, T\) are the pressure, specific energy and temperature for electrons (subscript \(e\)) and ions (subscript \(i\)). Coefficients of electron thermal conductivity \(\kappa\) and electron-phonon/ion energy coupling \(\gamma\) are described by the wide-range expressions [8]. The laser light absorption \(Q_L\) at an arbitrary profile of high-frequency permittivity is calculated using the Helmholtz wave equation solved by means of the transfer-matrix method [9]. The permittivity is described by the Drude model for temperature below the Fermi one, while for high-temperature non-degenerate electron states the plasma model is used [10]. For completeness of the model (1)–(4), we use the two-temperature multi-phase equation of state of aluminum [11–13] with the Thomas–Fermi expression for the thermal contribution of electrons [14].

3. Results and discussion

We perform modeling of different available experimental data for verification of the numerical model. In each simulation, we use a Gaussian time profile of the incident pulse in the following form \(I(t) = I_L \exp[-\ln(16)t^2/\tau_L^2]\). Milchberg et al performed experiment of self-reflation of S- and P-polarized laser pulses and measured the reflectivity dependence on the peak laser intensity \(I_L\), see figure 1. The results show the decrease of reflectivity for both S- and P-polarized pulses.
Figure 2. Results of experiment of Price et al [3] and simulation. Parameters of the pulse are: $\lambda_L = 400$ nm, $\tau_L = 120$ fs, $\theta = 0^\circ$.

Figure 3. Results of experiment of Fedosejevs et al [5] and simulation. Parameters of the pulse are: $\lambda_L = 248$ nm, $\tau_L = 250$ fs, $I_L = 10^{14}$ W/cm$^2$.

up to $\approx 10^{14}$ W/cm$^2$. For higher intensities $I_L > 10^{14}$ W/cm$^2$, it is seen that the reflectivity starts to grow, and similar dynamics is observed for simulation results. As one can see in figure 1 the agreement between experiment and simulation is very close in all range of intensities. For a wider range of intensities (from $10^{13}$ to $10^{16}$ W/cm$^2$) and normal incidence of high-contrast subpicosecond laser pulses, the absorption dynamics is presented in figure 2.

It is seen that for intensities up to $\approx 2 \times 10^{14}$ the absorption increases. Such dynamics can be explained by flattening of the electron density profile (growth of the characteristic plasma density
scale length) and electron subsystem heating when the frequency of electron-ion collisions grows. However, the frequency of electron-ion collisions has an upper limit associated with the interatomic distance \([15]\). Therefore, there is a maximum of absorption at \(I_L \approx 2 \times 10^{14} \text{ W/cm}^2\). For even higher intensities, the electron temperature reaches hundreds of eV and the frequency of collisions drops in non-degenerated plasma with the temperature as \(T_e^{-3/2}\) \([16]\). Thus, one can see in figure 2 the decrease of integral absorption for experimental data and results of modeling.

Finally, we investigate the angular dependence of reflectivity coefficient for S- and P-polarized laser pulses at fixed laser intensity of \(10^{14} \text{ W/cm}^2\), see figure 3. For small and moderate angles of incidence, \(\theta \gtrsim 50^\circ\), the roughness of the target surface in the experiment could be the reason of slight mismatch in results.

4. Conclusions
In conclusion, we have developed the wide-range model for the description of aluminum plasma produced by intense subpicosecond laser pulses. The model takes into account laser energy absorption by the conduction band electrons, electron thermal conductivity, electron-ion coupling and hydrodynamic motion of matter. The model successfully describes a variety of experimental findings including the angular dependence of reflectivity of S- and P-polarized pulses, self-reflectivity change for a wide range of incident pulse intensity. A good agreement between experimental results and simulations gives possibility to use the model for prediction of plasma parameters in planned experiments and can help in optimization of experimental setups.

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