Simulation of single-, double- and multi-pulse laser ablation of metals

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Abstract. We present preliminary results of hydrodynamic modeling of the laser ablation of copper by femtosecond laser pulses in regimes of single-, double- and multi-pulse irradiation. It is demonstrated that in comparison to a single-pulse regime the double-pulse one with a short subnanosecond delay is less effective while multi-pulse ablation with a subnanosecond intraburst is more effective. We show that multi-pulse ablation produces deeper crater in comparison with single-pulse or double-pulse regimes of the same energy.

1. Introduction
Subpicosecond laser systems are widely used in both fundamental science [1] and applications. In the last case, the efficiency of laser ablation can play a paramount role. To gain the ablation rate per energy unit, several approaches such as pulse tailoring or kHz multi-pulse ablation have been proposed. However, a breakthrough was achieved quite recently when a succession of hundreds of subpicosecond pulses with an intraburst repetition rate up to several GHz [2] was used for laser ablation. In this extraordinary regime, an increase of ablation efficiency by an order of magnitude was observed giving hope for the creation of more efficient techniques of laser–matter processing. Numerical simulation can help to follow an ultrafast ablation dynamics and understand an interplay between processes in irradiated media. Thus, optimal parameters can be determined. Recently, we demonstrated that the effectiveness of the multi-pulse ablation of aluminum increases with the repetition rate growth approaching the subnanosecond delay between successive pulses [3].

In this study, we present results of hydrodynamic modeling of femtosecond laser interaction with copper target in regime of single-, double and multi-pulse, and explain observed in the experiment growth of ablation efficiency.

2. Computational method
We investigate dynamics of bulk metal targets irradiated by ultrashort laser pulses with the use of a two-temperature hydrodynamic model:

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

\[ \frac{\partial u}{\partial t} + \frac{\partial (P_{\text{ion}} + P_{\text{el}})}{\partial m} = 0, \]
Figure 1. Contour plots of the density for single-pulse ablation (a); double-pulse ablation with 1 ns interpulse delay (b); 25-pulse burst with 108 MHz intraburst repetition rate (c); 50-pulse burst with 216 MHz intraburst repetition rate (d). In panel (a) SW is the shock wave, l+g is the liquid–gas phase state, liq is the liquid phase and solid is the solid phase state. All results were obtained for total fluence of 30 J/cm$^2$.

\[
\frac{\partial e_{\text{ion}}}{\partial t} + \rho_{\text{ion}} \frac{\partial u}{\partial m} = \frac{\gamma_{ei}(T_{\text{el}} - T_{\text{ion}})}{\rho},
\]

(3)

\[
\frac{\partial e_{\text{el}}}{\partial t} + P_{\text{el}} \frac{\partial u}{\partial m} = \frac{\partial}{\partial m} \left( \rho_{\text{el}} \frac{\partial T_{\text{el}}}{\partial m} \right) - \frac{\gamma_{ei}(T_{\text{el}} - T_{\text{ion}})}{\rho} + \frac{Q_L}{\rho}.
\]

(4)

Here $\rho$ is the material density, $t$ is the time, $m$ is the mass coordinate, $u$ is the velocity, $P$, $e$, $T$ are the pressure, specific energy and temperature, respectively. The indices “ion” and “el” denote electron and ion species, respectively. The electron–ion energy coupling is described by the corresponding term with the factor $\gamma_{ei}(\rho, T_{\text{el}}, T_{\text{ion}})$, and the electron heat transfer is specified by the thermal conductivity coefficient $\kappa_{ei}(\rho, T_{\text{el}}, T_{\text{ion}})$.

For calculation of the laser heating, $Q_L(t, z)$, we solve the Helmholtz wave equation for the laser electric field envelope $E$:

\[
\frac{\partial^2 E}{\partial z^2} + \frac{\omega_L^2}{c^2} \varepsilon(z) E = 0.
\]

(5)

Here $\omega_L$ is the laser frequency, $c$ is the speed of light and $\varepsilon(\omega_L, \rho, T_{\text{el}}, T_{\text{ion}})$ is the permittivity. Wide-range models of thermal conductivity coefficient, dielectric function and electron–ion coupling for copper is similar to ones used for aluminum [4].

Finally, we use a two-temperature multi-phase equation of state (EOS) [5,6] with the Thomas–Fermi expression for the thermal contribution of electrons [7] to describe the thermodynamic properties of copper out of electron–ion thermal equilibrium. Using this multi-phase EOS, we
account for melting and evaporation as well as thermodynamic properties of target material in metastable states. Kinetic model of nucleation [8] is used for the description of melted surface spallation.

3. Results and discussion

Using the numerical model, described above, we perform simulation of laser ablation in single-pulse, double-pulse and multi-pulse regimes. We choose the total fluence of incident pulses to be 30 J/cm$^2$.

Applying a single-pulse with such a fluence, we obtain a picture of laser ablation accompanied by formation of melted layer of about 500 nm and spallation of a liquid layer of approximately 440 nm thickness, figure 1(a). It is clear that the thickness of the ablated layer is much more than the skin layer, and thus, this layer will totally shield the target from succeeding pulses.

When we apply a double-pulse, the dynamics of ablation changes. Two pulses have a fluence of 15 J/cm$^2$ each and are separated by 1 ns delay, figure 1(b). While the first pulse produces the crater depth of about 250 nm, the second one interacts with the ablated layer and gives rise to suppression of ablation. The reheated layer evaporation results in deposition of previously ablated matter back to the target at about 1.2 ns delay. The resulting ablation depth is even less than that under the action of a single-pulse of 15 J/cm$^2$ fluence.

Application of a 25-pulse succession (108 MHz repetition rate) produces a more accurate ablation dynamics, figure 1(c). The melting depth reaches $z \approx 3 \mu$m for this case while the ablation depth is about 0.66 $\mu$m.

Finally, the 50-pulse burst with the fluence of each pulse of 0.6 J/cm$^2$ results in deepest ablation depth of about 0.85 $\mu$m that is approximately two times more effective than the single-pulse ablation. The dynamics of the crater growth for 1, 2, 25 and 50 pulses is presented in figure 2. We also summarize the obtained results to demonstrate changes in the final crater depth, figure 3.
4. Conclusion

Using the two-temperature hydrodynamic model closed by the wide-range EOS for copper, we calculate the ablation dynamics of bulk copper targets irradiated by single, double and multiple pulses of the same total energy. Simulations show that the laser ablation depth increases with the repetition rate growth in the multi-pulse regime while single- and double-pulse ablation are not so effective. The double-pulse ablation demonstrates that the crater depth drops when a massive liquid layers move out of the target and shields it from the next pulse. The higher effectiveness can be achieved only for pulses with the fluence below the threshold when each pulse remove a slight amount of matter in a liquid–gas phase. This portion of the target surface is ablated and becomes transparent for the next pulse. Thus, the residual heating near the surface plays a key role in ultrafast GHz ablation in a near critical point regime.

References

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