Sequences of Sub-Microsecond Laser Pulses for Material Processing: Modeling of Coupled Gas Dynamics and Heat Transfer

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Featured Application: Material processing by pulsed lasers can suffer from plasma ignition, which reduces efficiency. This work compares the conditions at single- and multipulse laser processing and proposes a modeling tool to optimize the sequences of pulses.

Abstract: Multipulse laser processing of materials is promising because of the additional possibilities to control the thickness of the treated and the heat-affected zones and the energy efficiency. To study the physics of mutual interaction of pulses at high repetition rate, a model is proposed where heat transfer in the target and gas-dynamics of vapor and ambient gas are coupled by the gas-dynamic boundary conditions of evaporation/condensation. Numerical calculations are accomplished for a substrate of an austenitic steel subjected to a 300 ns single pulse of CO2 laser and a sequence of the similar pulses with lower intensity and 10 µs inter-pulse separation assuring approximately the same thermal impact on the target. It is revealed that the pulses of the sequence interact due to heat accumulation in the target but they cannot interact through the gas phase. Evaporation is considerably more intensive at the single-pulse processing. The vapor is slightly ionized and absorbs the infrared laser radiation by inverse bremsstrahlung. The estimated absorption coefficient and the optical thickness of the vapor domain are considerably greater for the single-pulse regime. The absorption initiates optical breakdown and the ignition of plasma shielding the target from laser radiation. The multipulse laser processing can be applied to avoid plasma ignition.

Keywords: multipulse laser processing; heat transfer; gas dynamics; laser evaporation; laser plasma

1. Introduction

Pulsed laser processing of materials has some advantages over continuum-wave processing because it can offer thinner processed and heat-affected zones and higher surface temperatures. The serious drawback of laser pulses with durations ranging from nanoseconds to microseconds is the ignition of plasma. The plasma shields the treated surface from the laser beam. Thus, the efficiency of laser treatment decreases with the pulse energy. High repetition-rate sequences of pulses is a well-known solution to increase the efficiency [1–4].

The computational model developed by Vora et al. [2] to understand the influence of multiple millisecond laser pulses on the surface finish is in agreement with experimentally observed surface roughness [2]. Ranjbar et al. [3] numerically simulated the dynamics of vapor plumes induced by nanosecond multi-pulse laser irradiation in the burst mode. They showed that the multi-pulse mode can considerably decrease the plasma ignition threshold and increase the efficiency of ablation.
Cai et al. [4] modeled laser processing by the sequences of sub-millisecond pulses. Their model provided a theoretical guidance for optimizing the process parameters of laser ablation.

The complex of physical phenomena related to the interaction of a laser pulse with material includes absorption of laser radiation, heat transfer in the irradiated target followed by melting and evaporation, vapor expansion and interaction with the ambient gas, and laser beam absorption in the vapor, which can result in optical breakdown and plasma ignition. They were studied experimentally [5–9] and analyzed theoretically [9–18]. The above works indicate that the evaporation process is very important in laser processing. First, it is responsible for laser ablation. Conventional surface evaporation and phase explosion (volumetric evaporation) are the principal mechanisms for nanosecond pulses [19]. It seems that the phase explosion is more important for higher energies and shorter pulses while the surface evaporation becomes the principal ablation mechanism for longer pulses [2]. Due to high latent heat, evaporation can be the principal mechanism of heat loss. Thus, it influences heat transfer in the target. Finally, low ionization potential and high temperature of metal vapor facilitate optical breakdown [16], which drastically changes the mode of laser/material interaction. The surface temperature is the principal parameter influencing the rate of evaporation. This is why one can decouple gas dynamics and heat transfer in the target [19] under certain conditions. Generally, evaporation from the target surface and back condensation from the gas phase are competing processes [20]. Thus, the net evaporation rate depends also on the gas-phase parameters.

Gas dynamics of vapor and ambient gas coupled with heat transfer in the target was calculated by Bird’s direct Monte Carlo simulation (DSMC) [12,13,18]. If the mean free path in the gas phase is small, the numerical solution of Euler’s gas-dynamic equations is useful [10,11]. A strongly non-equilibrium Knudsen layer is formed in the gas phase near the target surface [20–27]. Rigorous boundary conditions at the Knudsen layer should be taken into account [15]. Gas-dynamic modeling of laser ablation [9–18] shows formation of a shock wave in the ambient gas and a contact temperature jump between the vapor and the ambient gas. The results of these calculations describe plume expansion and shock wave propagation at nanosecond pulsed laser ablation in ambient gas, which were observed experimentally [5,7]. Net back condensation of the vapor is expected at later stages of the gas-dynamic flow when the laser pulse is over [15].

The DSMC of laser evaporation by the sequences of nanosecond pulses [3] indicated that the second and the following pulses generate shock waves not only in the ambient gas but also in the vapor formed by the previous pulses. The pulses of the sequence are interdependent because of accumulation of heat in the target and because the gas parameters near the evaporating surface depend on the previous pulses [3]. If the inter-pulse separation time increases, the ablation depth decreases while the ignition of laser plasma becomes less probable [3]. The time of gas-phase relaxation after a laser pulse is shorter than that of target relaxation. Therefore, at high inter-pulse separation, the only mechanism of pulse interaction is the accumulation of heat in the target. For example, at modeling the sequences of millisecond pulses with inter-pulse separation of the order of 10 ms [2], the mutual influence of pulses through the gas phase was reasonably neglected.

Cai et al. [4] studied surface heat treatment by laser pulses of 1064 nm wavelength, 210 ns duration and the inter-pulse separation of the order of 10 µs. A rigorous model of conductive heat transfer in the target was proposed [4]. The dynamics of vapor and ambient gas was not considered in detail while simple models for evaporation and vapor ionization were used to take into account the shielding of the target by laser plasma. The model was validated by comparison with experimental results. The models with rigorous gas dynamics are known [3,15] but they were applied to nanosecond laser pulses.

A strong interdependence between heat transfer in the target and gas dynamics of vapor and ambient gas at laser–matter interaction was clearly realized back in the 1990s. The first models of heat transfer coupled with gas dynamics indicated the importance of the boundary conditions at the interface between the target and the gas phase [10,11]. Under the conditions of strong overheating and intensive evaporation, the near-boundary region of the gas phase (Knudsen layer) is highly non-equilibrium. Thus, the key issue is not gas dynamics but kinetic processes in the gas phase. In the first models,
the kinetic description of the gas phase was used in the framework of DSMC [12,13]. Such an approach has been successfully applied to nanosecond laser ablation up to now [3]. However, the DSMC computation becomes extremely time consuming at small Knudsen numbers. This is why it is not applied in the recent models for sub-microsecond [4] and millisecond [3] laser pulses.

The present work implements a rigorous but less time-consuming computation model where the interface region of the Knudsen layer is considered explicitly [15]. It concerns modeling the sequences of CO$_2$-laser pulses with 10.7 μm wavelength, the duration of 300 ns, and inter-pulse separation of 10 μs, which are promising for high-efficiency surface heat treatment [28]. Estimation of the ionization degree [27] and especially modeling the optical breakdown [4,16] require strong assumptions. To obtain conclusions that are more general, we restrict our consideration to qualitative effects of laser–plasma interaction. The calculation results obtained are rigorous before plasma ignition only. Note that both experiments and modeling [4,16] indicate that plasma ignition instantly interrupts the laser beam. It should be avoided at laser processing. The goals of the present study are to estimate the threshold of evaporation, the parameters of the vapor important for plasma ignition, and the physical mechanisms governing the mutual influence of the pulses in the multipulse sequences. The fraction of laser energy absorbed in the gas phase depends on its optical thickness. This is why the probability of plasma ignition is assessed by the optical thickness.

2. Model

In this model, heat transfer in the target and the dynamics of the ambient gas and the vapor are coupled through the boundary conditions at the interface. Only the central region of the laser spot is considered where the laser energy flux is supposed to be uniform. The thermal and the gas-dynamic responses are also uniform over this domain. Thus, the problem is essentially one-dimensional, at least at the initial stage of laser–material interaction. The position of the evaporating surface is not fixed, its recession velocity $u_s$ being consistent with gas-dynamic and temperature fields. Recession velocity due to laser evaporation is much smaller than the characteristic gas-dynamic velocities [15]. Therefore, it is neglected in the gas-dynamic problem considered in half-space $z > 0$ of the frame where the positive direction of axis Z is the external normal to the target surface approximated by plane $z = 0$ and the origin is fixed at the surface (see Figure 1). By contrast, the recession can influence heat transfer in the target [15] considered in half-space $z < 0$.

![Figure 1. Interaction between the laser beam, the target, and the gas phase.](image_url)
and the gas-dynamic equations for vapor and ambient gas. The heat transfer and gas dynamics are coupled by the gas-dynamic boundary conditions of evaporation/condensation [26].

2.1. Governing Equations

Heat conduction is supposed to be the principal mechanism of heat transfer in the target and is described by the heat equation in enthalpy form [14,15],

$$\frac{\partial h}{\partial t} + u_s \frac{\partial h}{\partial z} = \frac{\partial}{\partial z} \left( \lambda \frac{\partial T}{\partial z} \right)$$  \hspace{1cm} (1)

where \( h \) is the enthalpy per unit volume, \( t \) the time, \( \lambda \) the thermal conductivity, and \( T \) the temperature. The second term in the left hand side of Equation (1) is responsible for advection in the frame-moving relative medium. In the case of net evaporation, the interface recesses, the medium of the target moves in the positive direction of axis \( Z \), and \( u_s > 0 \). In the case of net condensation, the interface rises, the medium of the target moves in the negative direction of axis \( Z \), and \( u_s < 0 \). The volumetric specific heats in solid \( c_s \) and liquid \( c_l \) phases are approximately taken as constants. Then, the thermal equation of state [14],

$$T = \begin{cases} 
\frac{h}{c_s} & , \quad h \leq c_s T_m \\
T_m & , \quad c_s T_m < h < c_s T_m + q_m \\
\frac{T_m (h - c_s T_m - q_m)}{c_l} & , \quad h \geq c_s T_m + q_m 
\end{cases} \hspace{1cm} (2)$$

relates the enthalpy and the temperature, where \( T_m \) is the melting point and \( q_m \) the latent heat of melting per unit volume.

Gas-dynamic equations of continuity (3) and (4), momentum (5) and energy (6) [15],

$$\frac{\partial n_v}{\partial t} + \frac{\partial (n_v u)}{\partial z} = 0 \hspace{1cm} (3)$$

$$\frac{\partial n_s}{\partial t} + \frac{\partial (n_s u)}{\partial z} = 0 \hspace{1cm} (4)$$

$$\frac{\partial (\rho u)}{\partial t} + \frac{\partial (\rho u^2 + p)}{\partial z} = 0 \hspace{1cm} (5)$$

$$\frac{\partial (E + \rho u^2/2)}{\partial t} + \frac{\partial [u(E + \rho u^2/2 + p)]}{\partial z} = 0 \hspace{1cm} (6)$$

are applied at \( z > 0 \), where \( n_v \) and \( n_s \) are the number densities of vapor and ambient gas, respectively, \( u \) the gas velocity, \( \rho \) the gas density, \( p \) the pressure and \( E \) the internal energy per unit volume. In the gas mixture [15],

$$\rho = m_o n_v + m_g n_g \hspace{1cm} (7)$$

$$p = (n_v + n_g) kT \hspace{1cm} (8)$$

$$E = \left( \frac{n_v}{\gamma_v - 1} + \frac{n_g}{\gamma_g - 1} \right) kT \hspace{1cm} (9)$$

where \( m_o \) and \( m_g \) are the molecular masses and \( \gamma_v \) and \( \gamma_g \) the adiabatic exponents of vapor and ambient gas, respectively.

Mass balance at the interface, \( z = 0 \), is [15]

$$n_t u_s = n_v u_s \hspace{1cm} (10)$$

where \( n_t \) is the number density in the target. If laser energy is absorbed at the target surface with the heat effect per unit time per unit area equal to absorbed laser energy flux \( K_a \), the energy balance at \( z = 0 \) is [15]
where $T_s$ is the temperature of the target surface and $U$ the binding energy of target atoms at $T = 0$. Note that gas temperature at the interface $T(0)$ is necessary to calculate the right hand side of Equation (11). Temperature $T(0)$ is generally different from $T_s$ because of a temperature jump across the Knudsen layer formed near the interface at strong evaporation or condensation. Binding energy $U$ is the principal part of the latent heat of evaporation $q_v$. In addition to Equations (10) and (11), two boundary conditions at $z = 0$ are necessary at evaporation and only one boundary condition is applied at condensation [26].

Gas-dynamic boundary conditions of evaporation/condensation relate the parameters of target surface with the parameters of vapor formed at the outer edge of the Knudsen layer. The target parameters are its surface temperature $T_s$ and saturated vapor pressure $p_s$ at $T_s$. The saturated vapor pressure is estimated by integrating the Clausius–Clapeyron equation in assumption that the latent heat of evaporation $q_v$ is independent of temperature [14]

$$p_s = p_a \exp \left( \frac{q_v}{kT_b} - \frac{q_v}{kT_s} \right),$$

where $T_b$ is the boiling temperature at atmospheric pressure $p_a$. The thickness of the Knudsen layer at strong evaporation/condensation is about few mean free paths [26]. It is neglected in this work. Therefore, gas parameters, such as temperature $T$, pressure $p$ and Mach number $M$ are taken at $z = 0$. For example, the Mach number is defined as [15]

$$M = \frac{u(0)}{\sqrt{\gamma v kT(0)m}},$$

At evaporation $M > 0$ while at condensation $M < 0$. Boundary conditions of strong evaporation/condensation were obtained by gas-kinetic calculations of the Knudsen layer [20–26]. Analytical boundary conditions used in this work approximate the above cited rigorous calculations under the conditions typical for laser processing [15]. Evaporation and condensation are distinguished by comparing gas pressure $p$ and saturated vapor pressure $p_s$. At evaporation, $p < p_s$, the two boundary conditions are [15]:

$$M = 1 - \left( \frac{p}{p_s} \right)^{-0.275},$$

$$\frac{T}{T_s} = \frac{T_0 - (p_0)^{-0.125} + (1 - T_0)(p/p_s)^{-0.125}}{1 - (p_0)^{-0.125}},$$

where $p_0 = 0.20742$ is the pressure ratio and $T_0 = 0.6437$ the temperature ratio at evaporation with $M = 1$. Note that $M > 1$ is impossible at evaporation [20–26]. At condensation, $p > p_s$, the boundary condition is [15]

$$-M = 1 - \left( \frac{p_s}{p} \right)^{\alpha},$$

where parameters $\alpha$ and $I_0$ are functions of temperature ratio $T/T_s$ specified in [15].

### 2.2. Computations

Partial differential Equations (1), (3)–(6) with boundary conditions at the interface given by Equations (10), (11), (14)–(16) are solved in computation domains shown in Figure 1 by the numerical method of finite volumes on uniform grids. The parameters of undisturbed ambient gas are imposed on the top boundary of the gas-phase domain. Ambient temperature $T_a$ is the boundary condition
at the bottom of the target domain. When the shock wave approaches to the top of the gas-phase domain or the heat-affected zone approaches to the bottom of the target domain, the corresponding computation domain is enlarged, the grid is rearranged, and the discrete fields from the previous grid are interpolated to obtain new discrete fields on the new grid. Thus, the computation domains are always greater than the disturbed zones, and the influence of the external boundaries is excluded.

Differential Equations (1), (3)–(6) are approximated by second order in space- and first order in time-explicit finite difference equations. A second-order Godunov scheme [29] is used for gas-dynamic Equations (3)–(6). Central differences are applied to the spatial derivatives of heat Equation (1).

The present work uses original software for the thermal model of laser ablation, which was developed earlier [15]. The details of the numerical method and the calculation algorithm are given elsewhere [15].

3. Results

Laser treatment of austenitic steel X18H10T by pulsed CO₂ laser in an air atmosphere is modeled. The parameters of the target and the ambient gas are listed in Tables 1 and 2, respectively. Binding energy $U$ from Equation (11) is approximated by latent heat of evaporation $q_v$. The temporal profile of the laser pulse is specified by a triangle with the increasing front of $\tau_f = 50$ ns and the decreasing back of $\tau_b = 250$ ns (see Figure 2). The maximum of intensity $I_{\text{max}}$ is a variable parameter. It is attained at 50 ns after the pulse beginning. To exclude the uncertainty due to the absorptance of the target, the absorbed part of laser energy $K_a$ is specified as the model parameter. In the energy balance, Equation (11), it is explicitly defined as the following function of time:

$$K_a = \begin{cases} 
I_{\text{max}} \frac{t}{\tau_f}, & 0 < t < \tau_f \\
I_{\text{max}} \frac{\tau_f + \tau_b - t}{\tau_b}, & \tau_f < t < \tau_f + \tau_b
\end{cases} \quad (17)$$

Table 1. Properties of steel X18H10T accepted for modeling [30].

| Property                        | Value   |
|--------------------------------|---------|
| Melting point, $T_m$ (K)       | 1750    |
| Boiling point, $T_b$ (K)       | 3200    |
| Latent heat of melting, $q_m$ (GJ/m³) | 2.18    |
| Latent heat of evaporation, $q_v$ (GJ/m³) | 49.7    |
| Specific heat in solid phase, $c_s$ (MJ/(m³ K)) | 4.25    |
| Specific heat in liquid phase, $c_l$ (MJ/(m³ K)) | 5.95    |
| Thermal conductivity, $\lambda$ (W/(m K)) | 20      |
| Density, $\rho$ (kg/m³)       | 7890    |
| Atomic mass, $m_v$, (a.m.u.)   | 55.85   |
| Adiabatic exponent of vapor, $\mu_v$ | 5/3     |

Table 2. Properties of air accepted for modeling.

| Property                        | Value   |
|--------------------------------|---------|
| Ambient pressure, $p_a$ (atm.) | 1       |
| Ambient temperature, $T_a$ (K) | 298     |
| Density at the ambient conditions, $\rho_0$ (kg/m³) | 1.185 [30] |
| Atomic mass, $m_g$, (a.m.u.)   | 29 [30] |
| Adiabatic exponent, $\mu_g$   | 7/5 [30] |

The pulse parameters are listed in Table 3.

Figures 2–4 show the effect of a single pulse with the maximum absorbed intensity $I_{\text{max}} = 15$ MW/cm². Figure 2 shows the temporal profile of the laser pulse specified by the function
of absorbed laser power $K_a$ versus time $t$. Figure 3 shows temperature fields in the target calculated for this pulse. Surface temperature attains the boiling point $T_b$ and becomes greater than $T_b$. Therefore, an intensive vapor flow is formed along with a compressible flow of ambient air. Figure 4 shows gas-dynamic fields. Notice a shock front separating undisturbed and disturbed domains of air and a contact jump between air and vapor. The shock front is very close to the boundary of the computation domain for $t = 0.2$, $0.3$, and $1$ µs. Those are the instances just before the enlargement of the domain and the rearrangement of the computation grid. The shock front never touch the right boundary. At $t = 0.1$ and $0.2$ µs (see Figure 4), gas-dynamic velocity $u$ is positive at the interface $z = 0$ indicating net evaporation but at the end of the laser pulse at $t = 0.3$ µs, $u(0)$ becomes negative indicating net condensation. Figure 2 shows the dynamics of the surface temperature $T_s$ and the heat loss to evaporation calculated from the right hand side of Equation (11). One can see that the evaporation loss is much smaller than the absorbed laser energy for this pulse and the surface temperature can be considerably greater than the boiling point $T_b = 3200$ K.

![Figure 2](image)

**Figure 2.** Temporal profiles of the absorbed laser power, the surface temperature, and the evaporation loss for a single pulse with $I_{\text{max}} = 15$ MW/cm².

| Table 3 | Parameters of the laser pulse. |
|---------|-------------------------------|
| Duration (ns) | 300 |
| Inter-pulse separation (µs) | 10 |
| Absorbed intensity at the maximum, $I_{\text{max}}$ (MW/cm²) | 10 ... 15 |

![Figure 3](image)

**Figure 3.** Dynamics of the temperature field in the target for a single pulse with $I_{\text{max}} = 15$ MW/cm².

A single pulse with smaller intensity $I_{\text{max}} = 10$ MW/cm² cannot heat the target up to the boiling point (see the dotted line in Figure 5). However, the heat of the pulse is accumulated in the surface layer of the target. Figure 6 shows that at the moment of $t = 10$ µs after the pulse, the surface temperature is still about 600 K. The second pulse of the sequence starting at $t = 10$ µs, interacts with the already heated target. Therefore, it results in higher surface temperature (dashed line in Figure 5). The surface temperature becomes greater than the boiling point and evaporation starts. At the beginning of the third pulse at $t = 20$ µs, the surface temperature attains 800 K (see Figure 6a), the temperature after
the third pulse is higher (full line in Figure 5), and evaporation should be more intensive. Figure 6b shows the evolution of the temperature field in the target after the third pulse and Figure 7 presents the gas-dynamic fields. The gas-dynamic fields are qualitatively similar to the fields shown in Figure 4 for a single pulse with $I_{\text{max}} = 15 \text{ MW/cm}^2$. The maximum vapor pressure in Figure 4 is about 5 atm. while it is around 2 atm. In Figure 7. Therefore, one can conclude that evaporation is less intensive at $I_{\text{max}} = 10 \text{ MW/cm}^2$, even after the third pulse.

**Figure 4.** Evolution of the gas-dynamic fields at single-pulse laser processing with $I_{\text{max}} = 15 \text{ MW/cm}^2$. The arrow near each curve points to the corresponding axis. The axis title contains the name of the physical quantity. Flow velocity (dashed curves) and mass densities of vapor (red curves) and gas (blue curves): (a,c,e,g). Temperature (black curves) and pressure (blue curves): (b,d,f,h). Time $t$: 0.1 $\mu$s (a,b); 0.2 $\mu$s (c,d); 0.3 $\mu$s (e,f); 1 $\mu$s (g,h).
Figure 5. Increase of the surface temperature due to heat accumulation in the target at laser processing by the sequence of pulses with $I_{\text{max}} = 10\;\text{MW/cm}^2$ and the inter-pulse separation 10 $\mu$s.

Evaporation/condensation at the target surface is characterized by such parameters of the Knudsen layer as pressure ratio $p/p_s$, temperature ratio $T/T_s$, and Mach number $M$ related by the boundary conditions of evaporation/condensation, Equations (14)–(16). Figure 8 shows the evolution of these parameters at the studied regimes of laser processing. The effect of laser radiation on the target is characterized by the evolution of the temperature field shown in Figures 3 and 6 along with the melt depth in the target shown in Figure 9.
Figure 7. Evolution of the gas-dynamic fields after the third pulse of the sequence with $I_{\text{max}} = 10 \text{ MW/cm}^2$ and inter-pulse separation 10 $\mu$s. The arrow near each curve points to the corresponding axis. The axis title contains the name of the physical quantity. Flow velocity (dashed curves) and mass densities of vapor (red curves) and gas (blue curves): (a,c,e,g). Temperature (black curves) and pressure (blue curves): (b,d), (f,h). Time $t$: 20.15 $\mu$s (a,b); 20.2 $\mu$s (c,d); 20.3 $\mu$s (e,f); 21 $\mu$s (g,h).
Figure 8. Parameters of the Knudsen layer at evaporation/condensation at different regimes of laser processing: single pulse processing (a, b); multipulse processing (c, d). The arrow near each curve points to the corresponding axis: temperature ratio (black curves); Mach number (red curves); inverse pressure ratio (dashed blue curves).

Figure 9. Melt depth in the target at single pulse laser processing with $I_{\text{max}} = 15 \text{ MW/cm}^2$ and multipulse processing with $I_{\text{max}} = 10 \text{ MW/cm}^2$ and inter-pulse separation 10 µs.

4. Discussion

The modeling indicates that at inter-pulse separation 10 µs, the heat transferred to the target by a laser pulse is not completely dissipated when the next pulse of the sequence starts. Thus, thermal energy is accumulated in a near-surface layer of the target. It is illustrated by Figure 5 where the temperature curve of each pulse is above the temperature curve of the previous pulse. The intensity of evaporation by the pulses of a sequence increases because of increasing surface temperature.

In the modeled regimes of single and multipulse laser processing, the vapor velocity near the target surface becomes negative even before the termination of the 300 ns laser pulse (see Figures 4 and 7). Thus, back vapor condensation on the target surface starts. According to the model, all the evaporated material condenses back. The period of time necessary for full back condensation depends on the parameters of laser processing. The drop of the absolute value of Mach number $|M|$ down to zero in Figure 8 indicates the instant of complete back condensation. For single pulse with $I_{\text{max}} = 15 \text{ MW/cm}^2$ (see Figure 8b), it is $t = 1900$ ns. At $I_{\text{max}} = 10 \text{ MW/cm}^2$, the duration of back condensation is considerably less. For the second pulse (see Figure 8c), $t = 315$ ns. For the third pulse (see Figure 8d), $t = 415$ ns. In any
case, back condensation finishes well before the beginning of the next laser pulse at \( t = 10 \, \mu \text{s} \). This is why the laser radiation of the next pulse cannot interact with the vapor formed by the previous pulse.

Figure 8 shows that Mach number \( M \) approaches its theoretical limit for evaporation \( M = 1 \) \([20–22]\) but does not attain it. This is because of a relatively low laser intensity. Calculations by the similar model at higher intensities \([15]\) indicated that \( M = 1 \) can be attained. At evaporation, temperature ratio \( T/T_s \) and pressure ratio \( p/p_s \) are functions of \( M \) given by Equations (14) and (15). Note that the temperature ratio attains its minimum when evaporation is the most intensive (see Figure 8). At the stage of condensation, \( M \) tends to \(-1\) (see Figure 8). Note that supersonic condensation with \(|M| > 1\) is theoretically possible \([24,25]\). However, it is not observed in the present work as well as in the previous one \([15]\). For the calculated examples, temperature ratio at condensation is in the interval between 0.4 and 1 (see Figure 8). This means that the vapor is colder than the target. Such an unusual ratio is explained by adiabatic expansion of vapor where its temperature rapidly decreases as a power function of the density. The temperature of the target surface is controlled by heat conduction and decreases more slowly. Even if the vapor is colder, its pressure is still greater than the saturated vapor pressure at the temperature of the target surface. This is why condensation continues. Once the Mach number of the condensing vapor flow attains \(-1\), the value of \( M \) is around \(-1\) till the complete condensation of the vapor (see Figure 8). Similar behavior of the condensing vapor flow was observed at modeling for much shorter nanosecond pulses \([15]\).

Figure 9 shows the calculated dynamics of the melting/solidification front. The maximum melt depth estimates the thickness of the surface layer with the modified structure. This value appears to be approximately the same for the single laser pulse with \( I_{\text{max}} = 15 \, \text{MW/cm}^2 \) and for the sequence of three weaker pulses with \( I_{\text{max}} = 10 \, \text{MW/cm}^2 \) (see Figure 9). It is slightly greater than one micron. However, the parameters of vapor are quite different. Table 4 compares the parameters at 200 ns after the beginning of the single pulse with \( I_{\text{max}} = 15 \, \text{MW/cm}^2 \) (\( t = 0.2 \, \mu \text{s} \) in Figure 4) and the third pulse of the sequence with \( I_{\text{max}} = 10 \, \text{MW/cm}^2 \) (\( t = 20.2 \, \mu \text{s} \) in Figure 7). In both cases, the vapor temperature is about 3000 K. The vapor pressure at 15 MW/cm\(^2\) is four times the pressure at 10 MW/cm\(^2\). The thickness of the vapor domain at 15 MW/cm\(^2\) is four times its thickness at 10 MW/cm\(^2\). In summary, at the multipulse laser processing, vapor is considerably less dense and occupies a considerably thinner domain.

### Table 4. Calculated parameters of vapor.

| Parameter                                      | \( I_{\text{max}} = 15 \, \text{MW/cm}^2 \) | \( I_{\text{max}} = 10 \, \text{MW/cm}^2 \) |
|------------------------------------------------|------------------------------------------|------------------------------------------|
| Maximum absorbed intensity, \( I_{\text{max}} \) (MW/cm\(^2\)) | 15                                       | 10                                       |
| Time \( t \), (\( \mu \text{s} \))                  | 0.2                                      | 20.2                                     |
| Position of the contact surface, \( z \) (\( \mu \text{m} \)) | 75                                       | 18                                       |
| Vapor pressure, \( p \) (atm.)                   | ~8                                       | ~2                                       |
| Vapor temperature, \( T \) (K)                  | ~3000                                    | ~3000                                    |
| Target surface temperature, (K)                | 4200                                     | 3400                                     |

Metallic vapor is expected to be slightly ionized at the temperature of 3000 K. The source of charges is thermoelectron and thermoion emission from the target surface \([27]\). Modeling \([27]\) revealed the Knudsen layer and the sheath fused together at the interface between an evaporating surface and slightly ionized vapor. It was shown that the electronic temperature is around the surface temperature and the ionization degree is around the equilibrium one at the electronic temperature \([27]\). The last row of Table 4 shows the calculated surface temperature estimating the electronic temperature of the vapor. One can see that the electronic temperature is greater for the single pulse with \( I_{\text{max}} = 15 \, \text{MW/cm}^2 \). According to the Saha Equation \([31]\), the ionization degree sharply grows with the electronic temperature. Therefore, the ionization degree can be considerably greater at 15 MW/cm\(^2\). The principal mechanism of the absorption of infrared radiation in ionized gas is inverse bremsstrahlung \([31]\). The absorption coefficient is proportional to the concentration of electrons \([31]\).
The probability of optical breakdown in the vapor can be assessed from the optical thickness, which is roughly the vapor layer thickness (optical path) multiplied by the absorption coefficient of the vapor. Compare, for example, the distributions of vapor density at the end of the single laser pulse (see Figure 4, \( t = 0.3 \mu s \)) and at the end of the third pulse in the sequence (see Figure 7, \( t = 20.3 \mu s \)). The thickness of the vapor domain is about 140 \( \mu m \) in the former case and only 30 \( \mu m \) in the latter case. Thus, the optical path through vapor considerably reduces at the multipulse laser processing. One can see from these figures that the vapor density is around the density of the ambient gas in the former case and approximately a quarter of the ambient gas density in the latter case. The electron temperature and the ionization degree in the vapor are lower at the multipulse laser processing (see above). The electron density is the vapor density multiplied by the ionization degree. Therefore, the electron density along with the absorption coefficient considerably reduces at the multipulse laser processing. Finally, the optical thickness of the vapor considerably reduces too. The absorption initiates optical breakdown and the ignition of plasma shielding the target from laser radiation. Thus, the calculations indicate that at the multipulse laser processing, the vapor parameters are considerably less favorable for plasma ignition while the thermal impact on the target is essentially the same. This is why the multipulse processing can be applied to avoid plasma ignition.

The present work proposes a modeling tool, which gives tendencies and can be a guideline in experiments. To the best knowledge of the authors, the present work is the first where gas-kinetic processes are taken into account and analyzed for sub-microsecond laser pulses. The two examples considered show the contribution of different physical processes. Based on the achieved understanding of the competing processes, one can qualitatively estimate the influence of the laser parameters. For the given laser setup, only two parameters are variable: the pulse energy and the repetition rate. The modeling indicates that increasing the pulse energy sharply increases the optical thickness of the vapor, which results in optical breakdown. This is why increasing the pulse energy is not desirable. On the other hand, increasing the repetition rate above the 100 kHz considered here (corresponds to the 10 \( \mu s \) inter-pulse separation) will increase heat accumulation in the target at a much lower value of the optical thickness. Thus, the thermal impact on the target will increase while the probability of plasma ignition will be still low. Therefore, increasing the repetition rate above 100 kHz seems to be promising in order to increase the efficiency of the laser processing.

5. Conclusions

- Heat transfer in the target and gas dynamics of vapor and ambient gas coupled by gas-dynamic boundary conditions of evaporation/condensation are calculated for a single laser pulse with the maximum absorbed power density \( I_{\text{max}} = 15 \text{ MW/cm}^2 \) and a multipulse laser processing with \( I_{\text{max}} = 10 \text{ MW/cm}^2 \).
- The calculations indicate that the thermal impact on the target is essentially the same for the single pulse and the multipulse sequences. However, the vapor parameters are very different. Generally, evaporation is considerably more intensive at the single-pulse processing.
- Thermal impact on the target and evaporation become more intensive with an increase in the number of pulses in the sequence because of heat accumulation in the target.
- In the considered regimes, vapor formed during a laser pulse condenses back on the target surface during the time interval between consecutive pulses. Therefore, the pulses of the sequence can not interact through the gas phase.
- The modeling indicates that the absorption coefficient and the total optical thickness are considerably greater in single-pulse laser processing. The absorption initiates optical breakdown and the ignition of plasma shielding the target from laser radiation. Therefore, multipulse laser processing can be applied to avoid plasma ignition.

**Author Contributions:** Conceptualization, O.B.K.; methodology, A.V.G.

**Funding:** This research was funded by Russian Science Fundation grant number 18-19-00430.
Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

\( c \) specific heat
\( E \) internal energy per unit volume
\( h \) enthalpy per unit volume
\( I_{\text{max}} \) maximum laser energy flux
\( K \) laser energy flux
\( k \) Boltzmann constant
\( M \) Mach number
\( m \) molecular mass
\( n \) number density
\( p \) pressure
\( q \) latent heat
\( T \) temperature
\( t \) time
\( U \) binding energy
\( u \) velocity
\( z \) coordinate

Greek Symbols

\( \gamma \) adiabatic exponent
\( \lambda \) thermal conductivity
\( \rho \) mass density
\( \tau \) time interval

Subscripts

\( a \) ambient, absorption
\( b \) boiling, back
\( f \) front
\( g \) gas
\( l \) liquid
\( m \) melting
\( s \) solid, surface
\( v \) vapor

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