Quantum Electronics **43** (10) 943–948 (2013)

INTERACTION OF LASER RADIATION WITH MATTER. LASER PLASMA PACS numbers: 52.50.Jm; 52.50.Sw; 52.38.Mf
DOI: 10.1070/QE2013v043n10ABEH015141

Plasma formation on a metal surface under combined action of laser and microwave radiation

A.P. Gavrilyuk, N.Ya. Shaparev

Abstract. **By means of numerical modelling of the combined effect of laser (1.06 μm) and microwave (10^{10}–10^{13} s^{-1}) radiation on the aluminium surface in vacuum it is shown that the additional action of microwave radiation with the frequency 10^{12} s^{-1} provides complete ionisation of the metal vapour (for the values of laser radiation duration and intensity used in the calculations), while in the absence of microwave radiation the vapour remains weakly ionised. The mathematical model used accounts for the processes, occurring in the condensed phase (heat conduction, melting), the evaporation and the kinetic processes in the resulting vapour.**

Keywords: *laser radiation, microwave radiation, metal surface, plasma formation.*

1. Introduction

The action of laser radiation on a metal surface is accompanied by heating and evaporation of the material. At sufficiently high radiation intensities the breakdown of the metal vapour occurs and the plasma is produced. The conditions for plasma formation in a gas under the action of electromagnetic fields having various frequencies are studied well enough [1, 2]. It is also known that the use of the combined action of laser and microwave radiation on a gas provides a reduction in the plasma formation threshold as compared to using each of the radiations separately [3, 4]. One can expect that in the case of irradiation of a metal target this threshold will be also reduced, and the formation of plasma near the surface will be determined by the appropriate choice of the microwave radiation pulse parameters. The possibility to stimulate the high-density plasma formation by means of microwave radiation at the metal surface could reduce the required intensity of laser radiation or accelerate the process of plasma formation. Such control of the plasma formation process is interesting both for the study of laser radiation impact on metals and for the laser and plasma metal working technologies [5].

The aim of the present work is to justify the possibility in principle to stimulate the plasma formation using microwave radiation under conditions of optical laser radiation acting on a metal surface. The implementation of this effect is quite possible using the presently existing sources of laser [6, 7] and microwave [8, 9] radiation.

A.P. Gavrilyuk, N.Ya. Shaparev Institute of Computational Modelling, Siberian Branch, Russian Academy of Sciences, Akademgorodok, 660036 Krasnoyarsk, Russia;
e-mail: glyukonat@icm.krasn.ru, shaparev@icm.krasn.ru

Received 5 February 2013; revision received 22 April 2013
Kvantovaya Elektronika **43** (10) 943–948 (2013)
Translated by V.L. Derbov

2. Preliminary estimates

Consider laser radiation with the frequency ω_0 acting on the surface of a metal target. In the process of target heating and evaporating the atoms and electrons are produced. Then the electrons are heated by the laser radiation due to the inverse bremsstrahlung (i.e., the process of electron acceleration with absorption of the field energy) and begin to excite the atoms. The subsequent spontaneous decay of the atomic excited states results in the loss of the energy, acquired by the atoms from the electrons. This is an essential obstacle for heating the electrons and promoting the ionisation of atoms by electrons. However, at the sufficient concentration n_e of electrons, when the rate of atomic de-excitation by electron impact $K_{21}n_e$(K_{21} is the coefficient of the de-excitation rate) exceeds the effective spontaneous decay rate A_{21}^* (with the radiation trapping taken into account),

$$K_{21}n_e > K_{21}n_e^* = A_{21}^*, \tag{1}$$

the energy, spent by the electrons to excite the atoms, is returned to the electronic subsystem again. In this case the channel of electron energy loss related to the spontaneous decay becomes to play a minor role.

The inverse bremsstrahlung coefficient grows fast, as $\sim 1/\omega^2$ [1], with decreasing electromagnetic field frequency ω. Therefore, one should expect that the use of the microwave radiation with the frequency $\omega_m \ll \omega_0$ and relatively small intensity will lead to a more efficient heating of electrons and consequent ionisation of atoms up to the concentrations that satisfy condition (1). It is necessary to account for the fact that the microwave radiation stops to penetrate into the plasma region under the condition [1]

$$\omega_m < \omega_p = \sqrt{4\pi e^2 n_e/m}\,, \tag{2}$$

where ω_p is the plasma frequency; e is the elementary charge, and m is the electron mass. From Eqns (1) and (2) we conclude that to make this happen not earlier than the concentration value achieves n_e^*, the frequency ω_m has to satisfy the condition

$$\omega_m^2 \geqslant 3.2\times 10^9\,\frac{A_{21}^*}{K_{21}}. \tag{3}$$

At the same time, a significant increase in ω_m beyond the limit given by Eqn (3) is also undesirable, since in this case the microwave radiation absorption and the heating of electrons will be essentially reduced.

Thus, the additional action of microwave radiation will lead to faster heating of electrons, which may allow exceeding the threshold of atomic excitation and achieving the temperature, required to ionise the atoms. Correspondingly, the electron concentration will grow up to the critical value

$$n_{\rm cr} = \frac{m\omega_{\rm m}^2}{4\pi e^2} \quad (4)$$

[obtained from condition (2)], beyond which the microwave radiation stops to penetrate into the plasma region. Further heating of electrons is executed by laser radiation solely. If $n_{\rm cr} > n_{\rm e}^*$, then the energy of electrons that is irreversibly lost to excite the atoms becomes insignificant. This allows implementation of further complete ionisation of vapour atoms. To confirm the present conclusions we have performed numerical calculations based on the model of laser and microwave radiations interacting with the metal target and its vapour.

3. The model of radiation–target interaction

To describe the target heating and evaporation, as well as consequent ionisation of the vapour, we will use the approach, proposed in [10], with the additional effect of the microwave radiation taken into account. The model comprises the one-dimensional heat conduction equation within the region with the planar moveable boundary not known *a priori* [11] that separates the solid-state (i = S) and liquid (i = L) phases (Fig. 1) and is described by the expression

$$\rho_i(T_i)C_i(T_i)\frac{\partial T_i}{\partial t} = \frac{\partial}{\partial x}\left[\lambda_i(T_i)\frac{\partial T_i}{\partial x}\right], \quad (5)$$

where T_i is the temperature; $\rho_i(T_i)$ is the density; $C_i(T_i)$ is the heat capacity; and $\lambda_i(T_i)$ is the heat conductance. At the boundary (Γ) (Fig. 1) of the solid-liquid phase transition the Stephan conditions and the temperature equality condition are to be satisfied

$$\lambda_{\rm L}\frac{\partial T_{\rm L}}{\partial x} - \lambda_{\rm S}\frac{\partial T_{\rm S}}{\partial x} = \rho_{\rm S}L_{\rm m}V_{\rm m}, \quad T_{\rm m} = T_{\rm L} = T_{\rm S}, \quad (6)$$

where $V_{\rm m}$, $L_{\rm m}$, and $T_{\rm m}$ are the melting front velocity, the specific heat and the temperature of melting, respectively. Equations (5) and (6) are to be completed with the boundary condition on the metal surface that accounts for the balance of heat fluxes:

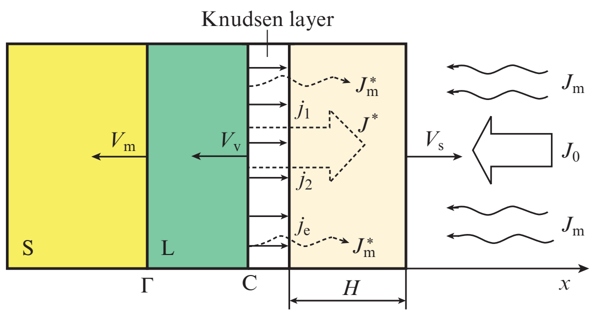

Figure 1. Schematic diagram of radiations acting of the metal surface. $J_{\rm m}^+$ is the intensity of the microwave radiation reflected from the metal surface.

$$\lambda_{\rm L}\frac{\partial T_{\rm L}}{\partial x} = \rho_{\rm L}L_{\rm v}V_{\rm v} - r_{\rm c}J^+, \quad (7)$$

where $L_{\rm v}$ is the specific heat of evaporation; $V_{\rm v}$ is the evaporation front velocity; J^+ is the laser radiation intensity passed through the gas layer and incident on the surface; and $r_{\rm c}$ is the coefficient of absorption of laser radiation by the surface.

To describe the phase transition between the condensed medium and the vapour (the boundary C in Fig. 1) we used the Knight evaporation model [12], by means of which from the equations expressing the conservation of mass, momentum and energy fluxes one can determine the gas dynamical characteristics of the vapours at the boundary of Knudsen' s layer:

$$p_{\rm K} = \rho_{\rm K}R_{\rm g}T_{\rm K}, \quad p_* = \rho_* R_{\rm g}T_{\rm c}, \quad u_{\rm K} = \sqrt{\gamma_{\rm a}R_{\rm g}T_{\rm K}/M},$$

$$T_{\rm K} = T_{\rm c}\left[\sqrt{1+\left(\frac{\sqrt{\pi}}{8}m_{\rm s}\right)^2} - \frac{\sqrt{\pi}}{8}m_{\rm s}\right], \quad m_{\rm s} = \sqrt{\frac{\gamma_{\rm a}}{2}}M_{\rm M},$$

$$\rho_{\rm K} = \rho_*\left[\sqrt{\frac{T_{\rm c}}{T_{\rm K}}}\left(m_{\rm s}^2 + \frac{1}{2}\exp m_{\rm s}^2 \operatorname{erfc} m_{\rm s} - \frac{m_{\rm s}}{\sqrt{\pi}}\right)\right. \quad (8)$$

$$\left. + \frac{1}{2}\frac{T_{\rm c}}{T_{\rm K}}(1 - \sqrt{\pi}\, m_s \exp m_{\rm s}^2 \operatorname{erfc} m_{\rm s})\right].$$

Here $R_{\rm g}$ is the universal gas constant; $M_{\rm M}$ is the Mach number; $T_{\rm K}$, $\rho_{\rm K}$, and $u_{\rm K}$ are the temperature, density and velocity of the gas at the exit from Knudsen's layer; M is the mass of the atom; ρ_* and p_* are the density and the pressure of saturated vapour; $\gamma_{\rm a}$ is the adiabatic exponent ($\gamma_{\rm a} = 5/3$); and $T_{\rm c}$ is the temperature of the metal surface.

To describe the processes that take place within the gas volume we used the lumped model, in which the variables (concentration, temperature, etc.) are averaged over the entire gas layer having the thickness H (Fig. 1). In turn, the value of H is determined by the motion of the outer boundary towards the vacuum with the velocity of sound

$$V_{\rm s} = \sqrt{\gamma_{\rm a}k_{\rm B}T/M}, \quad (9)$$

where $k_{\rm B}$ is the Boltzmann constant; and T is the temperature of atoms and ions.

The atom is modelled by a three-level system, comprising the ground (1), excited (2) and ionised (e) states. The temperatures of heavy particles (atoms and ions) are assumed to be equal. The plasma formation kinetics is described by the set of equations:

$$\frac{{\rm d}H}{{\rm d}t} = V_{\rm s},$$

$$\frac{{\rm d}n_{\rm e}}{{\rm d}t} = \frac{j_{\rm e}}{H} - n_{\rm e}\frac{\dot H}{H} + S_2n_2n_{\rm e} + S_1n_1n_{\rm e} - R_1n_{\rm e}^3 - R_2n_{\rm e}^3,$$

$$\frac{{\rm d}n_1}{{\rm d}t} = \frac{j_1}{H} - n_1\frac{\dot H}{H} + K_{21}n_2n_{\rm e} + A_{21}^*n_2 + R_1n_{\rm e}^3$$

$$- K_{12}n_1n_{\rm e} - S_1n_1n_{\rm e}, \quad A_{21}^* = \frac{A_{21}}{\sqrt{\pi\sigma_{12}n_1H/2}},$$

$$\frac{{\rm d}n_2}{{\rm d}t} = \frac{j_2}{H} - n_2\frac{\dot H}{H} + S_2n_2n_{\rm e} - A_{21}^*n_2 - K_{21}n_2n_{\rm e} +$$

$$+K_{12}n_1n_e + R_2n_e^3,$$

$$\frac{dT_e}{dt} = \frac{j_e}{Hn_e}(T_K - T_e) + \frac{2}{3k_B}\mu_b\frac{J}{n_e} + \frac{2}{3}\frac{1-r_m}{Hn_e}J_m \quad (10)$$

$$+\frac{2}{3k_B}E_{12}(K_{21}n_2 - K_{12}n_1) + \left(T_e + \frac{2}{3k_B}I_1\right)(R_1n_e^2 - S_1n_2)$$

$$+\left(T_e + \frac{2}{3k_B}I_2\right)(R_2n_e^2 - S_2n_2) - C_e(T_e - T),$$

$$\frac{dT}{dt} = \left(C_{ei} + C_{ea}\frac{n_e}{n_1+n_2}\right)(T_e - T) + \frac{j_1+j_2}{n_1+n_2}\frac{T_K - T}{H},$$

$$\mu_b \approx 0.1n_e\frac{\nu_{ea}+\nu_{ei}}{\omega_0^2}, \quad C_e = C_{ea} + C_{ei},$$

$$C_{ea} \approx \frac{2m}{M}\nu_{ea}, \quad C_{ei} \approx \frac{2m}{M}\nu_{ei}.$$

Here n_1, n_2, and n_e are the concentrations of unexcited atoms, excited atoms and electrons, respectively; T_e is the temperature of electrons; S_1 and S_2 are the electron impact ionisation rate coefficients for the normal and excited atoms; σ_{12} is the cross section of resonance radiation absorption; E_{12}, I_1 and I_2 are the atomic excitation energy and potentials of ionisation from the ground and excited state; K_{12} and K_{21} are the rate coefficients of excitation and de-excitation of atoms by electron impact; R_1 and R_2 are the coefficients of three-particle recombination with transition to the ground and excited state; A_{21}^* is the effective rate of spontaneous decay of the excited atomic states for the planar layer with the thickness H, determined in accordance with [13]; A_{21} is the atom spontaneous decay rate; μ_b is the coefficient of inverse bremsstrahlung for the laser radiation; the quantities C_{ea} and C_{ei} determine the elastic energy exchange between the electrons and the heavy particles (atoms and ions); ν_{ea} and ν_{ei} are the rates of electron–atom and electron–ion collisions; and j_1, j_2 and j_e are the flux density values for the evaporated normal atoms, excited atoms and electrons, respectively. In the equation for the temperature T_e the heating of electrons by laser and microwave radiation due to the inverse bremsstrahlung is taken into account by the second and the third terms, respectively, where r_m is the coefficient of reflection of the microwave radiation from the ionised region, the definition of which will be given below, and J_m is the microwave radiation intensity. The first term in the right-hand side of the second equation in the system of Eqns (10) accounts for the income of electrons due to thermionic emission from the metal surface, and the second term describes a decrease in the concentration of electrons due to the gas layer expansion. The same considerations are valid for the concentrations of atoms. The particle flux densities j_1 and j_2 were determined using the Boltzmann and Saha formulae with the temperature T_K at Knudsen's layer boundary, as well as the quasi-neutrality condition ($j_i \approx j_e$, j_i being the flux density of ions). Then

$$j_1 + j_2 + j_e = \frac{\rho_K u_K}{M}, \quad \frac{j_2}{j_1} = \frac{g_2}{g_1}\exp\left(-\frac{E_{12}}{k_B T_K}\right),$$

$$\frac{j_e^2}{j_1} = 2\left(\frac{m_e k_B T_K}{2\pi\hbar^2}\right)^{3/2}\frac{g_i}{g_1}\exp\left(-\frac{I_1}{k_B T_K}\right). \quad (11)$$

The intensity J, averaged over the gas layer thickness H that enters Eqns (10) is determined by solving the quasi-stationary transport equation $dJ/dx = -\mu_b J$ with the mean values of concentrations

$$J = \frac{J_0 + J^+ + J^* + J^-}{2}, \quad J^+ = J_0\exp(-\mu_b H),$$

$$J^* = J^+[1 - r_c(T_c)], \quad J^- = J^*\exp(-\mu_b H). \quad (12)$$

Here we use the following notations: J_0 is the intensity of the input laser radiation; J^+ is the intensity of the radiation passed through the layer with the thickness H and incident on the metal surface; J^* is the intensity of radiation, reflected from the surface; and J^- is the intensity of radiation at the exit from the layer having the thickness H.

When microwave radiation acts on a weakly ionised gas layer, a part of this radiation penetrates into it and a part is reflected from it. Besides, a minor fraction of the radiation passed through the layer can be absorbed by the metal surface. As a result, the fraction of the microwave radiation power absorbed by the plasma layer is determined by the coefficient

$$r = 1 - r_r - r_a, \quad (13)$$

where r_r is the reflection coefficient of the system 'plasma layer + metal surface'; and r_a is the coefficient that determines the fraction of microwave radiation absorbed by the metal surface. The coefficients r_r and r_a depend on the layer thickness H and the complex dielectric constants of the plasma (ε_2) and the metal (ε_3), which are defined by the expression [14]

$$\varepsilon_j = 1 - \frac{\omega_{pj}^2}{\omega_m^2(1 - i\Gamma_j/\omega_m)}, \quad j = 2, 3, \quad (14)$$

where ω_{p2} and ω_{p3} are the plasma frequencies of the considered vapour layer and the metal, and Γ_2 and Γ_3 are the corresponding collision rates that determine the relaxation rate of the electron distribution function. For the plasma layer $\Gamma_2 = \nu_{ea} + \nu_{ei}$[1)]. Note, that the first medium is vacuum, for which the dielectric constant $\varepsilon_1 = 1$. For given H the coefficient r is determined by the following expressions [15]:

$$r_r = \left|\frac{r_{12}\exp(2i\varphi) + r_{23}}{\exp(2i\varphi) + r_{12}r_{23}}\right|^2, \quad r_{12} = \frac{1-\sqrt{\varepsilon_2}}{1+\sqrt{\varepsilon_2}},$$

$$r_{23} = \frac{\sqrt{\varepsilon_2} - \sqrt{\varepsilon_3}}{\sqrt{\varepsilon_2} + \sqrt{\varepsilon_3}}, \quad \varphi = \frac{\omega_m}{c}H\sqrt{\varepsilon_2}, \quad (15)$$

where c is the velocity of light in vacuum. The absorption coefficient r_a has the form [16]

$$r_a = \left|\frac{d_{12}d_{23}\exp(-i\varphi)}{\exp(-2i\varphi) + r_{12}r_{23}}\right|^2, \quad d_{12} = \frac{2}{1+\sqrt{\varepsilon_2}},$$

$$d_{23} = \frac{2\sqrt{\varepsilon_2}}{\sqrt{\varepsilon_2} + \sqrt{\varepsilon_3}}. \quad (16)$$

1) When the degree of ionisation is smaller than 10^{-4} (i.e., when the role of microwave radiation is important), the rate ν_{ei} in the expression for Γ_2 can be neglected. Indeed, at $T_e > 0.3$ eV the ratio of the cross section of electron–ion collisions $\sigma_{ei} = (4\pi e^4\ln\Lambda)/(9k_B^2T_e^2)$ [2] to the cross section of electron–atom collisions $\sigma_{ea} \sim 10^{-15}$ cm^2 [2] will amount to less than 10^4. Therefore, $\nu_{ei}/\nu_{ea} < 1$.

4. Results of calculations

Using the present model, we have calculated numerically the effect of laser and microwave radiation on the aluminium surface. For the aluminium atom the 3P, 4S, 4D energy levels and the ionised state were taken into account. The values $\omega_{p3} \approx 2.25 \times 10^{16}$ s^{-1} and $\Gamma_3 \approx 1.25 \times 10^{14}$ s^{-1} for aluminium were taken from Ref. [14]. Figure 2 presents the time dependences of the concentration of atoms in the ground state (n_1), the total concentration of atoms in all excited states (n_2), the concentration of electrons n_e, the temperatures T_e of the electrons and T of the heavy particles (atoms and ions) under the action of a rectangular-shaped laser pulse having the duration $\tau_p = 5 \times 10^{-7}$ s and the intensity $J_0 = 2 \times 10^8$ W cm^{-2}. The laser radiation wavelength was $\lambda = 1.06$ μm. At the moment of time $t = 0$ the laser pulse was delivered onto the target and after the time interval $\tau_c = 3 \times 10^{-7}$ s the rectangular-shaped microwave pulse with the duration $\tau_m = 2 \times 10^{-7}$ s, the intensity $J_m = 10^5$ W cm–2, and the variable frequency ω_m was supplied.

From Figs 2a and 2b it is seen that in the absence of microwave radiation the vapours arising under the laser action remain weakly ionised. In this case the production of electrons is mainly caused by their thermal emission from the surface. At the initial stage, when the concentration of the vapours is small, their heating by the laser radiation is insignificant, the temperature of electrons is equal to that of the vapour and is determined by the temperature of the surface (Fig. 2b). With the growth of vapour concentration the absorption of the laser radiation increases and the electron temperature begins to grow. The main energy losses of the electrons are due to the vapour expansion and the transfer of energy to atoms in the process of inelastic collisions. With the growth of the electron temperature an additional channel arises for the energy losses related to the excitation of atoms followed by their spontaneous decay. These losses hamper (at moderate intensities of laser radiation) further heating of the electrons and stabilise their temperature at the values, insufficient for ionising the atoms by electron impact.

The additional use of microwave radiation aimed at heating the electrons leads to the growth of their temperature (Figs 2c, f, h). This is particularly strongly pronounced at $\omega_m = 10^{10}$ s^{-1} (Fig. 2d) and 10^{12} s^{-1} (Fig. 2f), when the fast growth of the electron temperature is observed that stops as the critical concentration of the electrons n_{cr} is attained. Then the fast decrease in the temperature follows due to the energy expenditure for the ionisation and heating of atoms. From the results obtained at $\omega_m = 10^{10}$ s^{-1} it follows that yet one more factor exists that stimulates the further growth of the electron concentration, namely, the excessive heating of electrons ($T_{e\max} \sim 90$ eV). At the microwave radiation 'cut-off' ($n_{cr} = 3.2 \times 10^{14}$ cm^{-3}), this energy, accumulated in the electronic system, is spent mainly for the ionisation of atoms, which leads to the fast increase in the electron concentration up to the value $n_e \sim n_{cr} T_{e\max}/I_1 \approx 5 \times 10^{15}$ cm^{-3}. At such concentra-

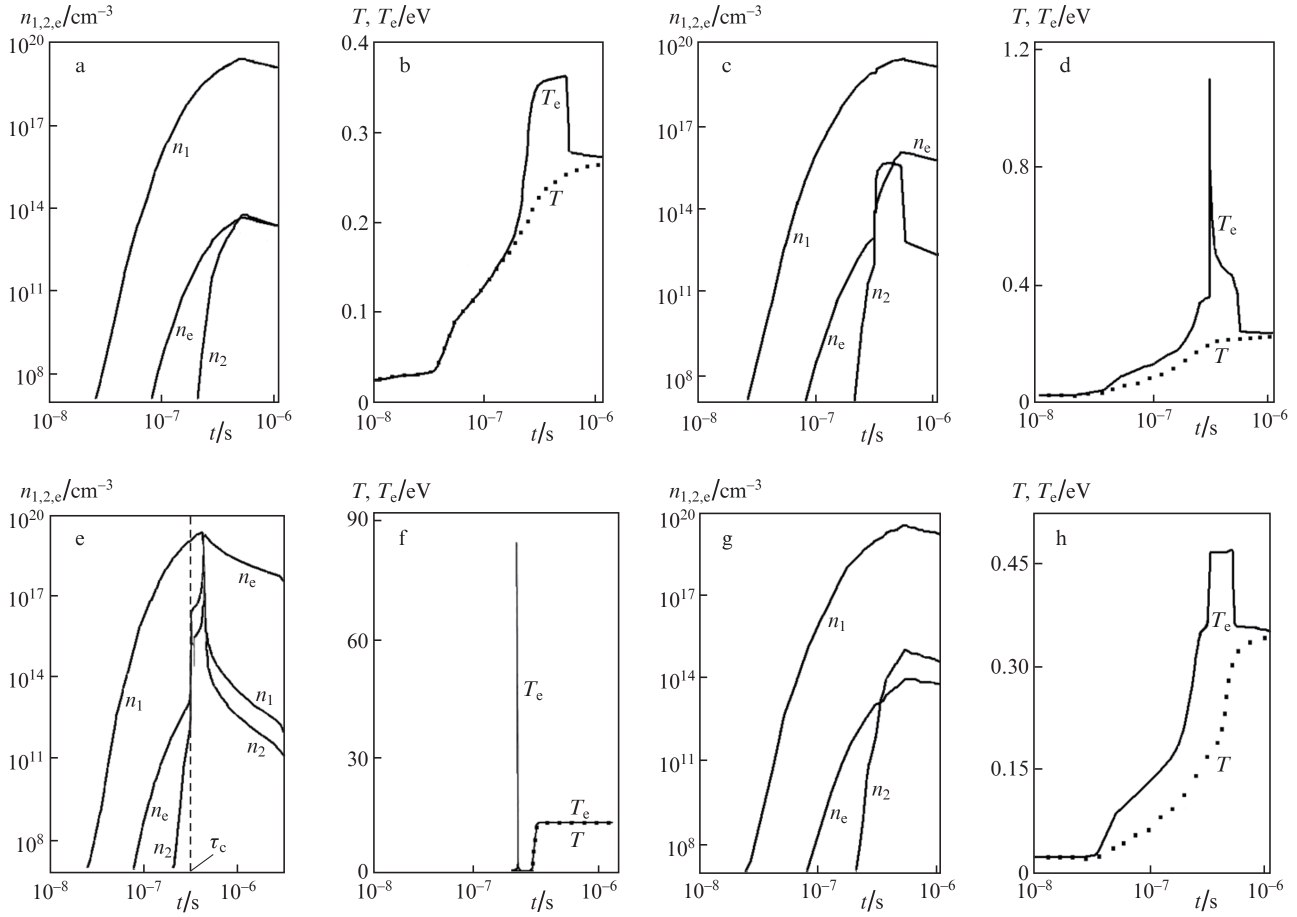

Figure 2. Concentration and temperature dynamics of the particles in the absence of the microwave radiation (a, b) and under the action of the microwave radiation having the frequency $\omega_m =$ (c, d) 10^{10}, (e, f) 10^{12} and (g, h) 10^{13} s^{-1}.

tions the main role begins to be played by electron–ion collisions, which leads to the growth of laser radiation absorption and further heating of electrons.

For better understanding of the obtained numerical results let us compare them with the theoretical conclusions presented above. As shown by the estimates, the main contribution to the electron energy losses is due to the atomic transition 3P–4S ($\lambda \approx 0.4$ μm). For this transition $K_{21} \approx 8 \times 10^{-8}$ cm^3 s^{-1} and $A_{21} = 1.5 \times 10^8$ s^{-1}. As follows from the numerical calculations, the concentration of normal atoms $n_1 \sim 10^{19}$ cm^{-3} is achieved during the action of the laser pulse. The thickness of the gas layer is $H \approx 0.06$ cm. Taking into account that at the present concentrations the main role is played by the resonance broadening of the absorption line corresponding to the mentioned transition, we arrive at the estimate of the absorption cross-section $\sigma_{12} \approx 1.4 \times 10^{-13}$ cm^2. Then we find the effective spontaneous decay rate A^*_{21} for the planar layer [13],

$$A^*_{21} = \frac{A_{21}}{\sqrt{\pi\sigma_{12}n_1H/2}} = 3.3 \times 10^5 \text{ s}^{-1}, \qquad (17)$$

and from Eqn (1) calculate $n^*_e \approx 4 \times 10^{12}$ cm^{-3}. At $\omega_m = 10^{10}$ s^{-1} (Figs 2c and 2d) the microwave radiation 'cut-off' occurs earlier ($n_{cr} = 3.2 \times 10^{10}$ cm^{-3}) than the concentration n^*_e is achieved, and condition (1) does not hold. Therefore, the effect of the microwave radiation on the vapour is small. It is worth noting that the very notion of 'cut-off' is rather conventional. Even at $n_e > n_{cr}$ the microwave radiation penetrates into the plasma region by the skin layer depth δ, heating the electrons. In Eqns (15) and (16) this effect is not taken into account.

At $\omega_m = 10^{12}$ s^{-1} (Fig. 2, e, f) we have $n_{cr} = 3.2 \times 10^{14}$ cm^{-3} $\gg n^*_e$ and the 'cut-off' (shown in Fig. 2e by a vertical dashed line) occurs when condition (1) is already certainly satisfied. In this case significant heating of electrons by the microwave radiation is produced, which allows increasing the degree of plasma ionisation. With the growth of the ionisation degree ($\geqslant 10^{-4}$) the main role in the absorption of laser radiation begins to be played by the electron–ion collision, which essentially increases the absorption of this radiation and, therefore, the rate of electrons heating.

At $\omega_m = 10^{13}$ s^{-1} (Fig 2, g, h) the absorption coefficient for the microwave radiation is significantly smaller than in the previous case, which does not allow further development of atomic ionisation by electrons.

The intensity of the microwave radiation is also important. The minimal value of the microwave radiation intensity, required for successful stimulation of plasma formation, can be roughly estimated from the balance between the energy, lost by the electrons to excite the atoms, and the energy, acquired from the microwave radiation,

$$2\mu_b J_{m\,min}/n_e = K_{12}n_1E_{12},$$

together with the condition that during the pulse the concentration must be able to attain the value

$$n^*_e \approx n_{e0}\exp(S_1 n_1 \tau_m).$$

Here for simplicity of estimating the absorbed microwave radiation energy we use the inverse bremsstrahlung coefficient μ_b. Then at $\omega_m = 10^{12}$ s^{-1} and $\tau_m = 2 \times 10^{-7}$ s for the concentration $n_1 \sim 10^{19}$ cm^{-3}, obtained by numerical calculation, we have the estimate $J_{m\,min} \sim 3 \times 10^4$ W cm^{-2}. At $\omega_m = 10^{10}$ and 10^{11} s^{-1} the radiation 'cut-off' occurs before the value n^*_e is attained.

At full ionisation of the vapours the absorption of laser radiation is significantly increased, which can lead to plasma screening of the target and reducing the fraction of laser radiation that reaches the target surface. This is well seen from the comparison of Fig. 2a and Fig. 2e. In the absence of the stimulating action of microwave radiation (Fig. 2a), when the degree of vapour ionisation is not high, the maximal vapour concentration is achieved at the end of the laser pulse. On the contrary, at full ionisation of the vapours (Fig. 2e), starting from the moment of time $t \approx 0.41$ μs a fast decrease in the total plasma concentration is observed prior to the laser pulse termination. This is explained by the growth of the plasma layer optical thickness and the increase in laser radiation absorption by plasma, which leads to the reduction of the target surface heating by this radiation. Indeed, at the plasma concentration $n_e \sim 10^{19}$ cm^{-3}, the electron temperature $T \approx 1$ eV, and the plasma layer thickness $H \approx 0.06$ cm, obtained in this regime, its optical thickness for the laser radiation amounts to ~20. The screening of the surface leads to the reduction of its temperature T_c and the thickness of the evaporated metal layer D_v, which is well seen in Fig. 3, where the horizontal lines mark the values of T_c and D_v in the absence of the microwave radiation.

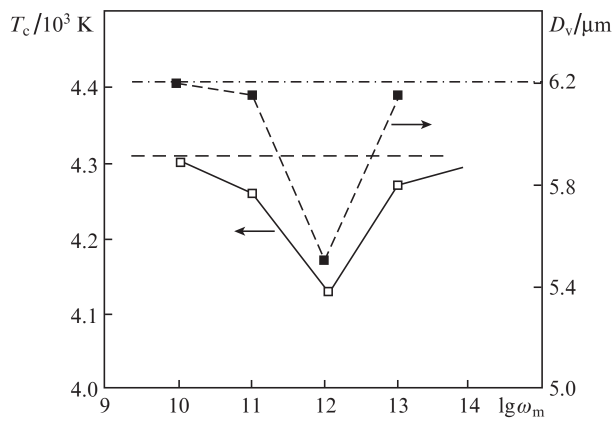

Figure 3. Dependences of the target surface temperature T_c and the evaporated layer thickness D_v on the microwave radiation frequency at the moment of pulse termination.

5. Conclusions

Thus, in the present paper it is shown that the additional action of microwave radiation with small intensity and certain frequency can lead to full ionisation of the target vapours at the intensities of the laser radiation, which are by one or two orders of magnitude smaller than those required for full vapour ionisation in the absence of microwave radiation. The role of the latter consists in efficient heating of the electrons and creating such concentration of them, at which the quenching of the excited atoms and their ionisation are implemented mainly by electron impact. At the same time, the intensity of laser radiation should be chosen such as to provide during the interaction time the production of vapour with sufficient density, for which the effective life time ($1/A^*_{21}$) of excited atomic states is considerably increased. Earlier plasma formation leads to the screening of the target against the laser radiation.

The use of the considered phenomenon seems to be most promising for the laser radiation of the visible or IR range, where the probability of multiphoton or tunnel ionisation of atoms by the radiation with moderate (smaller than 10^9 W cm^{-2}) intensity is not large. In the case of laser UV radiation, the two- and three-photon ionisation of atoms can lead to fast plasma formation [17, 18] even in the absence of the microwave radiation.

References

1. Raizer Yu.P. *Lasernaya iskra i rasprostraneniye razryadov* (Laser Spark and Discharge Propagation) (Moscow: Nauka, 1974).
2. Raizer Yu.P. *Gas Discharge Physics* (Berlin, New York: Springer, 1991; Moscow: Nauka, 1987).
3. Pokrovskaya I.E. *Zh. Tekh. Fiz.*, **46**, 1285 (1976).
4. Sokolov I.V. *Fiz. Plazmy*, **16**, 1513 (1990).
5. Veyko V.P., Smirnov V.N., Chirkov A.M., Shakhno E.A. *Lazernaya ochistka v mashinostroenii i priborostroyenii* (Laser Cleaning in Machine-Building and Instrument Engineering) (Saint-Petersburg: NIU ITMO, 2013).
6. Abilsiitov G.A., Golubev V.S., Gontar V.G., et al. *Tekhnologicheskiye lazery. Spravochnik* (A Handbook of Techology Lasers) (Moscow, Mashinostroyeniye, 1991) Vol. 1.
7. Eichler J., Eichler H.-J. *Laser, Grundlagen, Systeme, Anwendungen* (Berlin: Springer, 2006).
8. Rebrov S.I., in *Elektronnaya tekhnika. Ser. 1. SVCh-tekhnika*, vyp. 1, 31 (2009) [*Electronic Engineering. Ser. 1, Microwave Engineering*, Issue 1, 31 (2009)].
9. Denisov G.G., Zapevalov V.E., Litvak A.G., Myasnikov V.E. *Izv. Vyssh. Uchebn. Zaved., Ser. Radiofiz.*, **46** (10), 845 (2003).
10. Gavrilyuk A.P., Shaparev N.Ya., Yakubaylik O.E. *Kvantovaya Elektron.*, **20**, 828 (1993) [*Quantum Electron.*, **23**, 718 (1993)].
11. Mazhukin V.I., Samokhin A.A. *Matematicheskoe modelirovanie. Nelineynye differentsialnye uravneniya matematicheskoi fiziki* (Mathematical Modelling. Nonlinear Differential Equations of Mathematical Physics) (Moscow: Nauka, 1987).
12. Knight C.J. *AIAA J.*, **17**, 519 (1979).
13. Biberman L.M., Vorobyov V.S., Yakubov I.T. *Kinetika neravnovesnoi nizkotemperaturnoi plazmy* (Kinetics of Non-Equilibrium Low-Temperature Plasma) (Moscow: Nauka, 1982).
14. Prokhorov A.M., Konov V.I., Ursu I., Mikheilesku I.N. *Vzaimodeystvie lazernogo izlucheniya s metallami* (Interaction of Laser Radiation with Metals) (Moscow: Nauka, 1988).
15. Landau L.D., Lifshits E.M. *Electrodynamics of Continuous Media* (Oxford: Pergamon Press, 1984; Moscow: Nauka, 1992).
16. Kobak V.O. *Radiolokatsionnye otrazhateli* (Radar Reflectors) (Moscow: Sov. Radio, 1975).
17. Rosen D.I., Mitteldorf J., Kothandaraman G., Pirri A.N., Pugh E.R. *J. Appl. Phys.*, **53**, 3190 (1982).
18. Gavrilyuk A.P., Shaparev N.Ya., Yakubailik O.E. *High Power, Laser, and Particle Beams*, **6** (1), 91 (1994).