NUMERICAL SIMULATION OF THE KINETICS OF THE DENSE GAS BREAKDOWN BY THE LASER RADIATION NEAR A METAL SURFACE

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ABSTRACT

The optical breakdown of nitrogen investigated near a metallic target under the nitrogen pressure of 10 to 200 atm and the threshold values of the laser radiation intensity. The basic collisional gas reactions are analyzed and their contribution to the breakdown kinetics in estimated. The numerical results are compared with experiment.

I. INTRODUCTION

The interaction of the laser radiation of low density with metals when the ambient pressure is high (about 100 atm) is characterized by some peculiarities [1] . The laser radiation (λ =1.06 $\mu\kappa$, $G=(0.5-1)\times10^7 w/cm^2$, $\tau=(0.5-1)\times10^{-3}$ sec at the laser operation in the free generation mode) focused onto the metallic surface stimulates the formation of the plasma cloud near the target. For some metals (steel, Mo, Ti) the plasma cloud was formed without essential evaporation of the target material if the pressure of gases (N_2, He, Ar, Xe) remained above 50-70 atm. In those cases no mechanical damage of the surface was noticed [2,3] since the dense plasma cloud screened the metallic surface from the incident laser radiation. The radiated targets changed their physical properties under the action of the plasma cloud interaction with the metallic surfaces. For example, the steel microhardness was increased by a factor of 2-3 in the nitrogent plasma [2] . It was noted that in the plasma absence the laser radiation action reduced to usual heating of the metallic targets [4] . So the active medium, i.e. plasma, is required to change the surface properties.
It is rather difficult to obtain sufficient information about the formation and further development of the laser plasma experimentally because of the high pressure, the low transparancy of the plasma and a great many of high-speed processes. Experimental data on the initial stage of the plasma development - the optical breakdown of a cold gas - is especially hard to gain.

This paper is concerned with the kinetics analysis for the nitrogen breakdown by the laser radiation near the molybdenum surface.

2.MODEL

A laser beam (λ = I,06 mkm) is incident to the molybdenum plate. The cold gas is transparent to the laser radiation. The incident flux is partially reflected and some portion of it is absorbed. The surface is heated and the energy of emitted electrons is increased by breamsstrahlung. The breakdown dynamics is determined by elastic, inelastic and superelastic collisions with heavy particles. The mathematical model was based on the following elementary collisional processes:

$$N_2 + e \rightarrow 2N + e, \quad N_2 + N_2 \rightleftarrows 2N + N_2^{\#}, \quad N + 2N \rightarrow N_2^{\#} + N,$$

$$N_2 + e \rightarrow N_2^{\#} + e, \quad N_2 + e \rightleftarrows N_2^{*} + e, \quad N_2 + e \rightleftarrows N_2^{+} + 2e,$$

$$N_2^{*} + e \rightleftarrows N_2^{+} + 2e, \quad N + e \rightleftarrows N_2^{*} + e, \quad N + e \rightleftarrows N^{+} + 2e,$$

$$N^{*} + e \rightleftarrows N^{+} + 2e, \quad N^{+} + 2N_2 \rightleftarrows N_3^{+} + N_2^{\#}, \quad N_2^{+} + 2N_2 \rightleftarrows N_4^{+} + N_2^{*},$$

$$N_2^{+} + e \rightleftarrows 2N, \quad N_3^{+} + e \rightarrow 3N, \quad N_4^{+} + e \rightarrow 2N_2^{\#}.$$

All these processes are nonequilibrium, therefore the problem may be solved in a three-temperature approximation. The equations of chemical kinetics were supplemented by the energy balance equations for electrons and heavy particles; the vibrational energy of molecules was taken into account. The processes of diffusion and transport processes in the electric field of a spatial charge were also considered. The detailed description of the model was given in [5, 6] .

The thermoemission current was estimated by the Richardson formula. The influence of the electric field was taken into account by the equation , where is the additional work function due to the spatial charge potential u. Here u is determined from the Poisson equation.

The surface temperature was determined as a solution of the heat conductivity equation for a target material. The relations to connect one-side fluxes with their functions were given for the right-hand boundary being about IOO $\mu\kappa$ apart from the surface. The method of the numerical calculation was discussed in [7] .

3. DISCUSSION

Let us consider the basic features of the nitrogen optical breakdown. The typical distributions of the main nitrogent particle concentrations and temperatures are given in Fig. I at the time of breakdown $t_{np} \simeq 4.35 \times 10^{-9}$ sec and the pressure I00 atm for $G = 9 \times 10^{8}$ w/sm^{2}. Here N stands for atoms, N_2 for molecules, N^* and N_2^* for the electron-excited atoms and molecules, respectively, N^+ and N_2^+ for atomic and molecular ions, N_3^+ and N_4^+ for clusters, N_e for electrons, and T_e, T_k and T_g for the electron, vibrational and heavy particle temperatures, respectively. The jump in the temperatures T_e and T_k is typical of the breakdown zone. The increase of the vibrational temperature up to 4.5 ev leads to near complete dissociation (90%) of nitrogen in this zone; the electron-ion avalanche is effected in the atomic component of nitrogen. The molecular nitrogen breakdown does not occur due to large inelastic losses at high T_e. The electron temperature rise takes place at the point where the rate of Coulomb collisions $v_{ei} = 3.64 \times 10^{-6} T_e^{-3/2}$ sec^{-1} is comparable with the rate of electron-neutral collisions $\nu_{en} = v_e \sigma(\varepsilon_e) N$. The nitrogen breakdown is established conditionally by a maximum in the temperature T_e, which is equal to I.8 ev for p = I00 atm. The high-temperature zone propagates towards the laser beam under the action of transport processes. The rise in the temperature T_e results in the increase of the electron and ion concentrations, N_e and N_1^+; at the breakdown time $N_e \simeq N_1^+ \simeq 3 \times 10^{19}$ cm^{-3}.

The calculations have shown the important role of the molecule vibrational excitation reactions $N_2 + e \rightarrow N_2^* + e$, the thermal dissociation $N_2 + N_2 \rightleftarrows 2N + N_2^*$, the electron excitation of molecules and atoms $N_2 + e \rightleftarrows N_2^* + e$, $N + e \rightleftarrows N^* + e$, and the ionization of excited particles $N^* + e \rightleftarrows N^+ + 2e$, $N_2 + e \rightleftarrows N_2^+ + 2e$. Since the contribution of the assotiative ionization $N + N \rightarrow N_2^+ + e$ and the main state neutral ionization is negligible, these reactions are not taken into account in the problems with electron sources. The conversion reactions $N_i^+ + 2N_2 \rightleftarrows N_{i+2}^+ + N_2^*$ are also not important at $T_g \leq 0.2$ ev.

For the pressure p = I00 atm the breakdown threshold in the radiation density near the target is $G = 4 \times 10^{8}$ w/cm^{2} , the distance from the surface to the breakdown zone $x_{np} \sim 0.4 \mu\kappa$, the breakdown time $t_{np} \simeq 4.35 \times 10^{-9}$ sec. The values of G_{np} and t_{np} suggest that the gas breakdown is initiated by the spike of the laser pulse in experiment [I-3] . The surface temperature reaches 0.45 ev, which is not enough for the evaporation to develop at p = I00 atm.

The distance from the metallic surface to the breakdown zone x_{np}, the maximal electron temperature $T_{e\,max}$ and the breakdown time t_{np} dependences versus pressure P are shown in Fig. 2 for the same $G = 9 \times 10^{8}$ w/cm^{2}. The minimum on the t_{np}(p) curve at p= I00 atm indicates that this pressure creates most favourable conditions for evolution of the gas breakdown. The t_{np} (p) curve is qualitatively in good agreement with the G_{np}(p) curve obtained in experiment [8] , where the radiation density minimum was observed at p = 102 atm.

The calculations confirm the suggestion that the thermoemission is a possible breakdown mechanism at $p > 30$ atm. For lower pressures $p \sim 10$ atm the target material evaporation is important at the near-threshold intensities.

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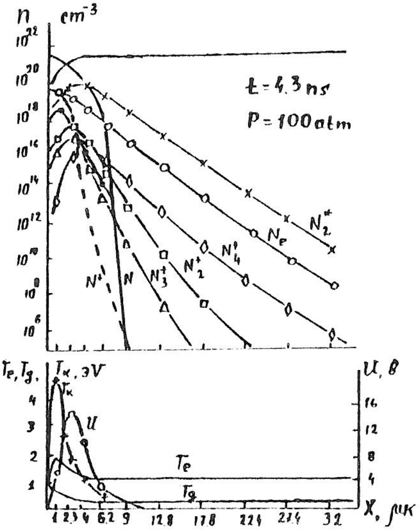
n cm⁻³
t = 4.3 ns
P = 100 atm
N₂⁺
Nₑ
N₄⁺
N₂⁺
N₃⁺
N
N⁺
Tₑ, T_g, T_κ, эV
U, B
T_κ
U
Tₑ
T_g
X, μк

Fig. 1

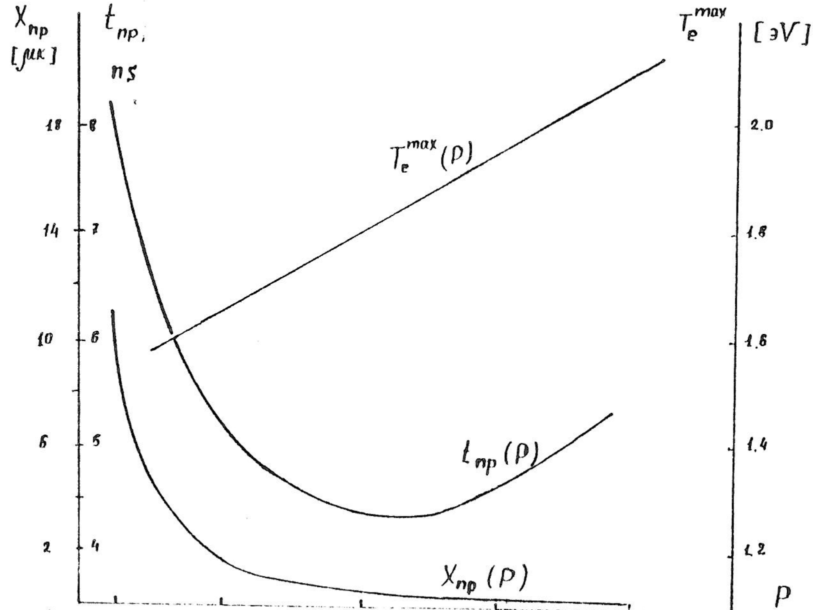
X_np [μк]
t_np, ns
Tₑ^max [эV]
Tₑ^max (P)
t_np (P)
X_np (P)
P [atm]

Fig. 2.