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ОСОБЕННОСТИ ВОЛН ПОГЛОЩЕНИЯ ЛАЗЕРНОГО ИЗЛУЧЕНИЯ ПРИ ОПТИЧЕСКОМ ПРОБОЕ ГАЗА

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PECULIARITIES OF WAVES OF LASER RADIATION ABSORPTION AT GAS OPTICAL BREAKDOWN

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В данной работе исследованы скорости распространения волн поглощения лазерного излучения (светодетонационной волны, быстрой волны ионизации (БВИ) и сверхзвуковой радиационной волны), в зависимости от интенсивности лазерного излучения при оптическом пробое в нормальной атмосфере.

In the present study, expansion velocities of absorption waves of laser radiation (laser supported detonation wave and fast wave of ionization and a supersonic radiative wave) are researched depending on intensity of laser radiation at optical breakdown in a normal atmosphere.

At the present time the following supersonic mechanisms of plasma fronts expansion are known: a fast ionization wave (FIW), laser supported radiation wave (LSRW), laser supported detonation wave (LSDW), breakdown and electronic thermal conductivity mechanism. The detailed description of the mentioned above mechanisms is given in Refs [1, 2]. The FIW is the least investigated among above-stated mechanisms. In the present moment the theory of the FIW is mainly developed for atomic gases, and velocity of discharge propagation in the FIW regime is the numerical solution of unwieldy system of equations including radiation transfer and ionization kinetics [2, 3]. As a rule, the most likely mechanism of ionization front expansion is the LSDW for sharp-focused laser radiation within intensities range of ~10^8–10^9 W cm^{-2} in a normal atmosphere, then as laser intensity increases the LSDW changes to the FIW [4]. Recently the study of mechanisms of laser plasma expansion is caused by following reasons: creation of laser ignition devices of mixtures of combustible gases and air; development of tunable microwave radiation sources [6]; examination of the spectral characteristics of laser plasma [8–11] and plasmas fronts interaction [10, 11] as well absorption coefficients of laser radiation for various mechanisms. We shall determine mechanism of plasma expansion towards the laser radiation for a case of an optical breakdown and low-threshold breakdown by laser wavelength $\lambda = 1.06$ μm within intensities range of $5\cdot10^8$–10^{11} W cm^{-2} in a normal atmosphere that corresponds to the experimental conditions of works [4, 10]. In a case of near-threshold laser intensities close to breakdown threshold of air ($I \sim (5–10)\cdot10^{10}$ W cm^{-2}), we are restricted to reviewing of a case of sharp-focused laser beam. Thus, the determination of plasma expansion mechanism is reduced to comparison of velocities of three mechanisms: the FWI, the LSDW and the LSRW (if, for given intensity, the certain mechanism provides the greatest velocity then plasma expands towards laser radiation in this mechanism). Where numerical results are given, we shall express focal spot radius R in cm, duration of laser pulse ф in ns, laser intensity I in W cm^{-2}.

LSDW velocity is represented in Ref [1] by

$$D = \left[\frac{2(\gamma^2 - 1)I}{\rho} \right]^{1/3}, \quad (1)$$

where г is air adiabatic index behind ionization front, с is air density before front.

The value of the lower bound of the FWI velocity $u_{\min}$ is determined by relation [6]

$$u > \frac{1}{zN_0} \int_{\varepsilon_i}^{\infty} d\varepsilon \int_0^1 d\mu \frac{\mu F_\varepsilon \sigma(\varepsilon)}{\sigma_a(\varepsilon)}, \quad I = 2N_0 u e(\overline{m}, T). \quad (2)$$

In this relation $N_0 = 2.69\cdot10^{19}$ cm^{-3}; $e(\overline{m}, T)$ is intrinsic energy of the gas behind front (counting upon 1 parent atom); $\overline{m}(T)$ is an average charge of plasma; e_i is the energy of the UV photon corresponding to a threshold of oxygen ionization; z, F_e are degree of ionization and flux of ionizing UV photons on the border of ionization front; $\mu \equiv \cos\vartheta$, $\sigma(\varepsilon) = 0.21\sigma_{iO_2}(\varepsilon) + 0.79\sigma_{iN_2}(\varepsilon)$ is total photoionization cross-section of the air ($\sigma_{iO_2}(\varepsilon)$ and $\sigma_{iN_2}(\varepsilon)$ are cross-sections of the molecular oxygen and nitrogen); $\sigma_a(\varepsilon)$ is total photoabsorption cross-section, defined similarly to photoionization cross-section. The value of the lower bound of FWI velocity was determined using following assumptions [6,7]: $F_\varepsilon \approx F_{\varepsilon b}$, $z=10^{-3}$, where $F_{\varepsilon b}$ is the equilibrium flux (UV photons flux from a surface of black body). However in a number of experiments [4, 10, 11], velocities of FWI were much less than the value of the lower bound determined by relation (2) with assumption (3). We registered velocity of the FWI $u = 200$ km s^{-1} for laser intensity $I \approx 10^{11}$ W cm^{-2}, while $u_{min} = 2\cdot10^3$ km s^{-1} determined for this intensity by relation (2) with assumption (3).

We register a strong radiation of the second positive system of nitrogen during ionization front expansion [11], layers absorbing plasma radiation and adjoining to ionization front emitted this radiation. Radiation of the second positive system of nitrogen gives the significant contribution to the common radiation of air plasma at temperatures 5000–7000 K. Thus in investigated range of laser intensities, $T^1 >> T^0$ and the contribution of $F^0_{\varepsilon b}$ into common flux of ionizing quanta is negligible. Assume that border of ionization front is a point on axis of laser beam, in which ionization by electronic impact much more exceeds photoionization, since the role of photoionization for FWI mechanism is reduced only to start electron avalanche [2]. According to [4] rates of electron avalanche and photoionization are equaled at degree of ionization before front $z \sim 10^{-3}$–10^{-2}, further electron avalanche rate exceeds photoionization. Thus, on the border of ionization front, at $z \sim 10^{-3}$–10^{-2}, the ionization photons flux for R <<1 cm is determined by relation (4) at x = 0. Velocity of ionization front in LSRW regime was defined using the set of equations described in work [3]

$$F_i = N_0 u z_0, I = 2N_0 u e(\overline{m},T). \quad (5)$$

Here z_0 is air degree of ionization corresponding to significant absorption of laser radiation ($z_0 \sim 3\cdot10^{-2}$–10^{-1}), F_i is flux of UV ionizing quanta. Results of calculations of ionization front velocities for three mentioned above mechanisms are presented on Fig. 1.

Equation (1) was used to calculate LSDW velocity. The lower boundary of FWI velocity u_{min} was determined triply: for R = 0.15 and R = 0.01 cm, in both cases $z = 3\cdot10^{-2}$, on the basis of equations (2), (4) at x = 0 and for flux from surface of black body (3) at $z = 10^{-3}$. Velocity of ionization front in LSRW mode was calculated twice: for $z_0 = 3\cdot10^{-2}$ and R = 0.01 cm, using formulas (4–6), and for $z_0 = 3\cdot10^{-2}$ and for flux from surface of black body using equations (5) and (7). Experimental points lay above the curves (Fig. 1) corresponding to lower boundary FWI velocity for all experimental conditions in which plasma front moves towards laser radiation as FWI[9–13]. Velocity of LSRW is less lower boundary of FWI velocity even at coincidence of degree of ionization $z = z_0$ = 0.03. For $I > 10^9$ W/cm^2 FWI is main mechanism of plasma front expansion.

Dependence of plasmas front velocities on time after breakdown was investigated explicitly in work[20], so time dynamics of plasma spectra is presented in this section. Spectra of air breakdown by 532 and 1064 nm laser radiation are shown in Fig. 2. Molecular bands corresponding to second positive system of nitrogen ($C^3{}_u$–$B^3{}_g$) against the high-intensity continuous background, dip of continuum intensity and absorption line of atomic oxygen O I 777 nm are observed during laser-plasma interaction, i.e. ionization front expansion. Dip is explained by absorptive transitions from the excited vibrational-rotational levels of the basic electronic state and from the excited electronic states of atmospheric gases molecules, these excited states lead to photodissociation of molecules. As was mentioned above the source of molecular nitrogen radiation is air layer adjoining to ionization front. The seed electrons for breakdown occur in this layer due to ionization by UV radiation and then molecules are excited, dissociated and ionized by these electrons. The molecular bands and dip of continuous spectrum intensity was not registered in other examined spectral ranges. "Lifetime" of oxygen absorption line and second positive system of nitrogen are similar and observed up to 70 ns. After laser pulse action registered spectrum is most likely attributable to emission line. The multiplet NII 333 was observed up to 500 ns after breakdown. Molecular bands and dip of continuum intensity are most expressed for breakdown by 532 nm radiation.

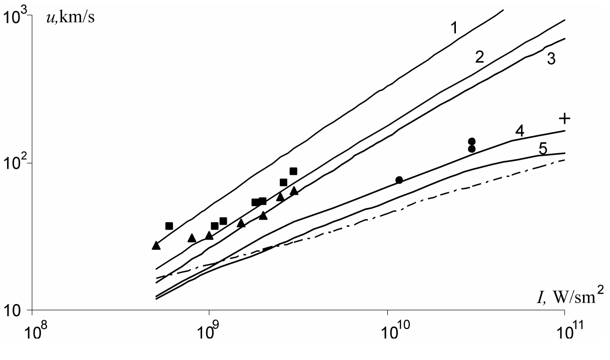

Fig. 1. Velocities of ionization front expansion depending on laser intensity: curves are calculation, dots is data of experiments. 1 is u_{min} FWI ($z = 10^{-3}$, black body), 2 – LSRW ($z = 3\cdot10^{-2}$, black body), 3 – u_{min} FWI ($z = 3\cdot10^{-2}$, R = 0.15), 4 – u_{min} FWI ($z = 3\cdot10^{-2}$, R = 0.01), 5 – LSRW ($z_0 = 3\cdot10^{-2}$, R = 0.01), dotted curve – LSDW. ■ – FWI velocity, $R \approx 0.15$[11,12], ▲ – FWI, $R \approx 0.02$[12], ● – FWI, $R \approx 0.01$[13], + – FWI, $R \approx 0.01$[9,10].

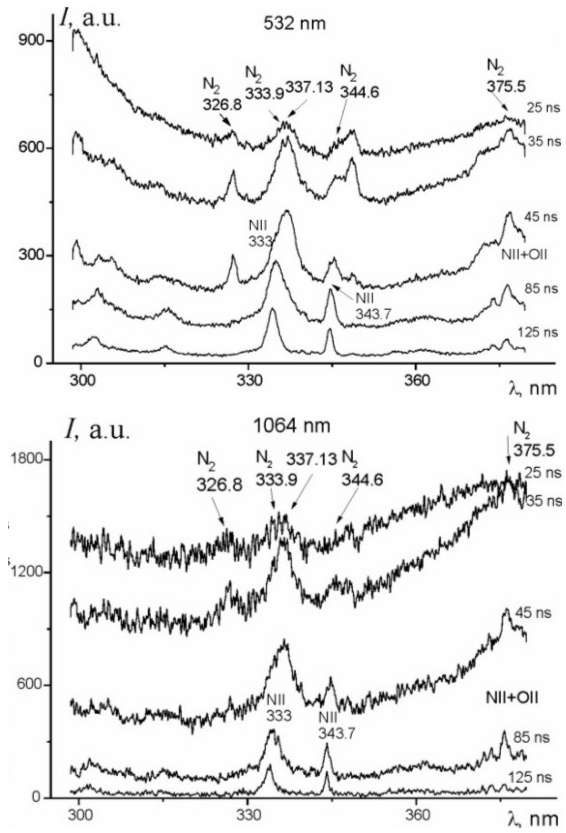

Fig. 2. Spectra of air breakdown by single pulse. To the left is breakdown by 532 nm laser radiation, to the right by 1064 nm.

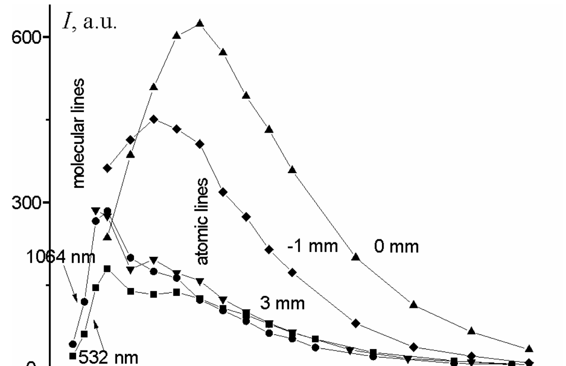

Fig. 3. Contrast of emission line л = 333 nm depending on time. ■ is single breakdown by 532 nm, ● single breakdown by 1064 nm; ▼ distance between focal points 3 mm, ▲ 0 mm, ♦ – 1 mm.

Contrast of emission line л = 333 nm for all mentioned above cases is shown in Fig. 4. For single breakdown emission line contrast is bigger for 1064 nm laser radiation up to 150 ns. There is no increase of emission line contrast for distance between focal points 3 mm. For other distances considerable magnification (up two times for 125 ns) is observed thus the maximal value of contrast is shifted to larger times.

Conclusions

The obtained results show, that spectral and temporal characteristics at colliding interaction of laser plasmas considerably differ from a case of non-interacting plasmas. The main mechanism of plasma expansion for л = 532 and 1064 nm with intensity above $I > 10^9$ W/cm^2 is FWI. The magnification of line and continuous spectrums intensities is registered but in such a manner that the contrast increases. The significant enhancement of a time interval with maximal contrast value is registered. Thus it is possible to considerably improve the sensitivity of LIBS in case of interacting laser plasmas using time delay up to 100 ns and time gate up to several hundreds ns or several μs depending on spectral line. Also it is necessary to take into account molecular bands and dip of continuum while carrying out LIBS measurements. For example, in our case the time delay must be about 100 ns to escape influence of molecular bands and dip of continuum in spectral range 300–375 nm.

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