EXPERIMENTAL INVESTIGATIONS OF LASER SPARK IN THE REGIME OF SLOW COMBUSTION

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The dynamics of variation in the temperature and the electron number density of a laser plasma in the regime of light–induced combustion is examined using the spectral method. The use of a double image converter (DIC) for recording the spectrum made it possible to obtain the resolution time of the order of 0.1 ms.

The fluctuations in the electron number density in discharge at a characteristic frequency of ~10 Hz *have been detected, and this indicates a lack of the strict local thermodynamic equilibrium (LTE) in plasma.*

Currently, the methods for remote sensing of the turbid atmosphere based on the use of an optical discharge initiated by a high–power laser pulse are rapidly developed. Optical discharge in air can be induced upon exposure to the millisecond pulses of a neodymium laser with comparatively low intensity under conditions when there exists an absorbing seed (e.g., the aerosols) in air. The parameters of such a discharge were examined in a number of papers. However, the dynamics of the variations in the temperature and the electron number density in the discharge in the regime of slow combustion have not yet been studied. In this paper we give the results of experimental investigation of this problem.

The appropriate method for diagnostics of plasma with the parameters $T = (1–2)$ eV and $n_e = (10^{17}–10^{17})$ cm^{-3} is evidently the spectral method, which has been successfully used in numerous investigations of plasma with the above–indicated parameters. In this paper we make use of this spectral diagnostics with photoelectric recording of the spectrum.

In order to initiate plasma, we used the technique proposed in Ref. 1. A capacitor with $C = 3.5$ μF charged up to 4 kV, was connected to two copper needles forming the discharge gap. The Nd–laser radiation was focused with a lens 25 cm in focal length. An electric breakdown in the discharger was initiated due to the evaporation of the metal from the needle surfaces. The seed plasma was picked up by the laser radiation and spread along the beam. The breakdown threshold corresponded to the laser pulse energy $E = 550$ J under these conditions. We worked in the regime with slight excess of the threshold value.

Photography was made in the wavelength range $\lambda = 300–400$ nm selected out with the help of the UFS–2 and S3S23 glass filters. This made it possible to eliminate to a considerable extent the extraneous illuminations, because this wavelength range corresponds to that of the maximum emissivity of a blackbody at the temperature $T \sim 10^4$ K. The laser spark photography is shown in Fig. 1.

A block diagram of the experimental setup for studying the spectrum dynamics of the plasma is given in Fig. 2. The image of the optical discharge at magnification $\Gamma \sim 1$ was formed in the plane of the input slit of the monochromator. The image axis was perpendicular to the slit 2 μm in height. The spectrum was recorded with the help of an Li–602 double image converter and an S9–8 storage oscillograph. The pulse train for starting up the laser, detector, and storage oscillograph with required delays was generated by a GI–1 pulse oscillator.

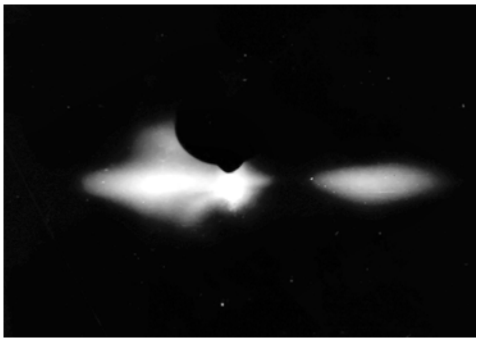

FIG. 1. Photography of the optical discharge exposed within the time over which the pulse acts.

For the use of the DIC did not deteriorate the spectral resolution, the width of the input slit of the monochromator was chosen so that the instrumental half–width of the converter $\lambda_i = \delta \cdot \frac{d\lambda}{dl}$ did not exceed the half–width of the instrumental function of the monochromator $\lambda_0 = S\frac{d\lambda}{dl}$, where $d\lambda/dl$ is the reciprocal linear dispersion of the monochromator, S is the width of the input slit, and δ is the spatial resolution of the DIC which was 10 lines per millimeter. In accordance with this, the width of the input slit S was equal to 0.1 μm.

The spectrum was scanned by applying a sawtooth voltage at the horizontally deflecting plates of the converter. The period of recording of the spectrum was equal to 50 ms and the measurement period was 100 ms. Thus, within the discharge lifetime one could carry out ~10 observations in the wavelength range under study. The electric signal from the DIC collector was amplified and recorded with the oscillograph. As is well known, for the characteristic plasma parameters (the electron number density n_e = 10 cm and $T \sim$ 1–2 eV) the Stark effect makes the main contribution to broadening of the spectral lines. Measuring the spectral line half–width and using the relation we obtain

$$\Delta\lambda_{1/2} = 2W\left(\frac{n_e}{10^{16}}\right) +$$

$$+ 3.5A\left(\frac{n_e}{10^{16}}\right)^{1/4}\left[1 - \frac{3}{4}N_D^{-1/3}\right]W\left(\frac{n_e}{10^{16}}\right),$$

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where A and W are the parameters describing the effect of line broadening and N_D is the total particle number inside a Debye sphere. Now we can determine the electron number density n_e (cm^{-3}). For the measurements we have chosen the O1 lines of oxygen (centered at $\lambda = 3947$ and $\lambda = 4368$) and the N 11 line of nitrogen (centered at $\lambda = 4552$). The choice of these lines follows the recommendations of Ref. 4 as well as the fact that these wavelengths are nearby the maximum in the spectral characteristic of the DIC photocathode.

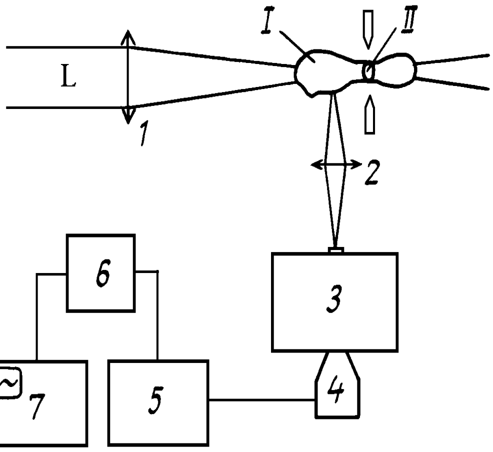

FIG. 2. Block diagram of the experimental setup for studying the spectrum dynamics of plasma: L refers to the radiation of a GOS–1001 laser, I – to t plasma of discharge, II – to tplasma seed initiating the breakdown spark. 1) lens with $f = 25$ cm, *2) INDUSTAR–51 objective lens; 3) CDMC monochromator; 4) LI–602 dissector; 5) control unit; 6) GI–1 pulse oscillator; 7) S9–8 storage oscillograph.*

The plasma temperature was determined from the ratio of the intensities of the spectral lines of the atoms with different multiplicity of ionization. For the calculations we used the relation

$$\frac{I_1}{I_2} = \frac{f_{mn}(1)\, q_n(1)\, \lambda^3(2)}{f_{mn}(2)\, q_n(2)\, \lambda^3(1)} \left(\frac{kT}{\chi_H}\right) \frac{\exp(-\Delta E/kT)}{4\pi^{3/2} a_0^3\, n_e},$$

where the number 1 refers to a higher ionization degree, a_0 is Bohr's radius, χ_H is the ionization energy for hydrogen, f_{mn} is the oscillator strength for the transition m, n, q_n is the statistical weight of the levels,

$$\Delta E = [E(1) - E(2)] + [\chi_i - \Delta\chi_i],$$

and χ_i is the ionization energy for an atom. Having measured the ratio I_1/I_2 and predetermined n_e, we can find the electron temperature.

In order to measure temperature, we have chosen the O1 and O11 lines of oxygen (centered at $\lambda = 4368$ and $\lambda = 4349$), sufficiently isolated and clearly delineated against the continuum background. In the spectrum under study these lines are spaced at a distance of 1.5 μm. This made it possible to record them simultaneously without significant losses of the information about each line, because the length of the working section of the dissector photocathode was 20 μm.

The temperature, determined in this way, is the temperature of electrons. The time for the electrons and ions to acquire the same temperature is of the order of $\tau = M/(m < v\sigma_M\, n_e >)$, where v is the electron velocity, σ_M is the effective cross section of an elastic collision between an electron and an atom or an ion with mass M, and m is the mass of an electron. The cross sections of ions are approximately identical: $\sigma_M = 3\cdot10^{-15} z^{-2}\, (z^2 E_H / kT)^2$.

The corresponding time of the temperature homogenization in the process of collisions with ions is $\tau = zM/3\cdot10^{-7} m (z^2 E_H / kT)^{3/2}\, n_e$. When $n_e \sim 10^{17}$ cm^{-3} and $T \sim 1$ eV, we have $\tau = 10^{-9}$ s. For this reason the time for the electrons and ions to acquire the same temperature is negligible for the above–indicated parameters of plasma and the temperature measured experimentally is equal to that of the ions.

The measurements were performed at the points located at the distances 4, 7, 10, 13, and 15 μm from the initiation point in the direction opposite to the laser beam. The least–squires technique was used to process the experimental data. The time dependence of the temperature of plasma at a distance of 10 μm from the focal point is shown in Fig. 3. It has been fitted by the forth–degree polynomial.

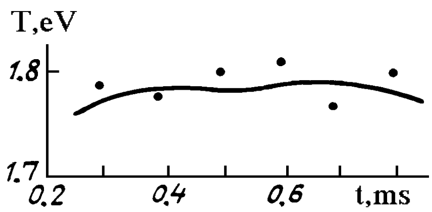

FIG. 3. Time dependence of the plasma temperature at a distance of 10 μm *from the focal point.*

Nearly the same shape exhibits the time dependences at the other points of discharge within the limits of the experimental error. The steady behavior of the temperature indicates that the stationary discharge was obtained for the conditions of our experiments with the temperature $T = 1.67$ eV being approximately constant in time and space. The time behavior of the electron number density is shown in Fig. 4. The value of the number density averaged over time was $n_e = 1.77\cdot10^{17}$ cm^{-3}. Sufficiently strong oscillations near this value can be seen which have a characteristic frequency of 10^5 Hz. The relative intensity of oscillations $\sqrt{<\delta n_e^2>}/n_e$ averaged over time and space is equal to nearly 20% which exceeds the experimental error of 12%.

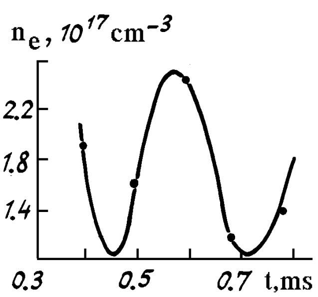

FIG. 4. Time dependence of the electron number density of discharge at a point located at a distance of 3 μm *from the focal point.*

The measured electron number densities and temperature of plasma were used for estimating the existence of the local thermodynamic equilibrium against the criterion proposed in Ref. 3. The estimates showed that the existent electron number density is sufficient for establishing the thermal equilibrium between the electrons and the excited levels. This enabled us to make a conclusion about the proximity of plasma to the local thermodynamic equilibrium. However, the occurrence of oscillations indicates a lack of the strict equilibrium. The departure from the local thermodynamic equilibrium can be estimated based on the intensity of oscillations. This is very important in constructing the model of discharge.

Note in conclusion that the results of this paper can be used in the researches on laser radiation transfer through the atmosphere, in the remote spectrochemical analysis of aerosols, and for optimization of conditions for the collective optical discharge in air.

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