Measurement of electronic temperature of laser-induced plasma channels at various pressures in argon by relative intensities of spectral lines

M A Tarasova, D A Kochuev, A F Galkin, D G Vasilchenkova, A S Chernikov, K S Khorkov and V G Prokoshev
Vladimir State University, 87 Gorky Street, Vladimir, 600000, Russia
E-mail:trsvmargarita@gmail.com

Abstract In this paper, we study the properties of laser-induced plasma channels formed by femtosecond laser radiation in argon. The electron temperature of the plasma channels is calculated by the method of relative intensities of spectral lines.

1. Introduction
Spectroscopic plasma research occupies a special place among the methods of plasma research. Plasma is considered as a particle system. In spectroscopic studies, the interaction between particles determines the main characteristics of the plasma.

The electrons in the field of an atom or ion can change their energy state, as a result of which radiation is generated. Free electrons emitting in the field of an atom or ion create a continuous plasma spectrum. Bound electrons, making the transition from one level to another, create a plasma line spectrum. Important plasma parameters, such as: temperature, electron concentration, frequency of collisions of atoms or molecules, plasma chemical composition, can be determined using spectroscopic measurement methods [1].

There is a plasma model when the plasma is in the so-called local thermodynamic equilibrium. When using this model, it is assumed that the collisions of particles with each other play a major role. An equilibrium is established, which is due to the fact that the particles, repeatedly colliding with each other, exchange energy. With any change in plasma, the corresponding distribution is almost instantly restored, this is due to very frequent collisions between particles.

Collisions cause the excitation of bound electrons in ions or atoms. The processes occurring in the plasma, a large number, and almost every one of them can be opposed to the reverse process. For example, de-excitation – excitation, recombination – ionization, etc. The rates of inverse and direct processes are equal, which corresponds to the principle of detailed balance. As a result, the distribution of electrons in energy levels corresponds to the distribution that occurs with complete thermodynamic equilibrium.

In this case, the number of excited atoms in which the external electron is at a level with energy E (measured from the ground state) is determined by the Boltzmann law:

$$N^* \sim N_0 \exp\left(-\frac{E}{kT_e}\right)$$

(1)
where \( k \) — the Boltzmann constant; \( N_0 \) — the concentration of molecules; the parameter \( T_e \) is the electron temperature, and the proportionality coefficient includes only atomic constants.

By measuring the number of excited atoms, one can determine the electron temperature. The number of excited atoms, in turn, can be determined by the number of photons emitted by them. In practice, as a rule, the intensity of the spectral line is measured, which is proportional to the number of emitted photons, and which means the radiation power of a given frequency emitted by the plasma at a certain solid angle, the value of which is given by the conditions of the experiment. Electronic temperature can be determined by the relative intensities of the lines, by comparing with each other. Formula (2) allows to calculate the electron temperature by the relative intensities of two lines:

\[
\frac{I_2}{I_1} = \frac{g_2 f_2 \lambda_2^4}{g_1 f_1 \lambda_1^4} \exp(-\frac{\Delta E}{kT_e})
\]

where \( \Delta E \) — the difference between the excitation energies of the lines under study, \( f \) — the oscillator power, \( g \) — the statistical weight of the level, \( \lambda \) — wavelength of the corresponding line of the spectrum.

In [2], the electron temperature of the plasma channel was measured by spectroscopic characteristics generated by femtosecond laser radiation in argon at atmospheric pressure, the temperature is about 5800 K. Many studies have been devoted to studying the characteristics of plasma channels [3-5].

2. Description of the experimental scheme

Yb:KGW femtosecond laser system was used as a source of laser radiation, which has the following parameters: wavelength \( \lambda = 1030 \text{ nm} \), pulse width \( \tau = 280 \text{ fs} \), pulse repetition rate \( f = 10 \text{ kHz} \), pulse energy \( \varepsilon_{\text{max}} = 150 \mu\text{J} \). The polarization of laser radiation is linear. The power of laser radiation during the experiments remained unchanged: the average power of 1.5 W; pulse power density \( \sim 10^{13} \text{ W/cm}^2 \).

An experimental scheme has been developed for studying the characteristics of plasma channels and measuring the plasma electron temperature using the method of relative intensity of spectral lines. The scheme of the experimental setup is shown in figure 1.

![Figure 1. The scheme of the experiment setup: 1 – femtosecond laser system; 2 – laser radiation; 3, 12, 8 – focusing lens; 4 – insulated vessel; 5 – the area of optical breakdown and the formation of a plasma channel; 6 – input and output windows in an isolated vessel; 7 – spectrometer; 9 – gas cylinder; 10 – gearbox; 11 – CCD camera; 13 – power meter.](image-url)
Femtosecond laser radiation (2) was focused into the internal volume of the developed vessel (4) using a focusing lens with a focal length of 150 mm. An optical breakdown is formed in the focal plane of the focusing lens. Registration of geometric characteristics and brightness of the luminescence was carried out with a CCD camera. The volume of the vessel was filled from a cylinder containing the necessary gas, the pressure in the vessel was controlled by a gearbox equipped with shut-off and measuring equipment. The study of the spectrum of the output radiation was carried out using a spectrometer (7). Data from the spectrometer and the CCD camera in the process of conducting experimental work were collected on a personal computer. Plasma spectrum were obtained at various pressures.

3. Results and discussion

Figure 2 shows the spectrum of argon with transitions corresponding to given wavelengths at normal pressure.

The spectral lines obtained were recorded at an exposure of 2 seconds. A long exposure time is necessary to obtain a good response of the spectrometer matrix and averaging the recorded signal.

The electron temperature was calculated on the basis of formula (2). The final formula for calculating the electron temperature is:

$$T_e = \frac{-\Delta E}{(\ln \frac{I_2}{I_1}) - \ln \left( \frac{g_2 f_2}{g_1 f_1} \cdot \left( \frac{\lambda_1}{\lambda_2} \right)^3 \right) k}$$

(3)

where $\lambda_1$ and $\lambda_2$ are the wavelength of the spectral line (nm) for calculations it is more convenient to use the most separated pairs of lines. For argon, the lines 415.85 nm and 852.14 nm were used.

Estimation of the electron temperature by the method of the relative intensity of spectral lines involves the use of a large number of spectral lines and finding the «average» value. In the process of
calculations, 3265 pairs of spectral lines were used, of which about 160 pairs of lines were selected using the following selection criteria: Positive value of the transition energy difference, satisfying the condition: \( \Delta E_1 - \Delta E_2 \approx 2 \), where \( \Delta E \) is the transition energy of the selected line; The positive value of the logarithm of the product of the statistical weight (g) and the oscillator strength (f), since otherwise the expression has no physical meaning; The resulting value of the electron temperature must be positive, otherwise the expression has no physical meaning; Required condition \( \Delta E \geq T_e \cdot 1.38 \cdot 10^{-23} \).

The spectral line intensity values were obtained from the spectrometer. The figure shows images of plasma channels in argon, obtained at different pressures. Images of plasma channels were obtained using a CCD camera, in accordance with the scheme. Based on figure 3, it can be concluded that with increasing pressure, the luminosity of the plasma channel increases, and its interesting feature is its shift relative to the direction of propagation of laser radiation.

The length of the plasma channels was determined by the images obtained from the camera. For this purpose, a standard was used with calibration objects applied on it of known dimensions, after which the dimensions of the standard and the length of the plasma channel were compared.

![Figure 3. Plasma channels images](image)

Figure 4 shows a graph of the plasma channel length of the pressure values.

![Figure 4. Graph of dependence of the plasma channel length on the pressure value](image)

Figure 5 shows the relative intensity lines depending on the pressure values. There is a tendency that the intensity increases up to the pressure of 8 bar, when this value is reached and the pressure increases further, the relative intensity of the lines decreases. This may be due to the fact that at first the number of particles (concentration) begins to grow, but since there is no change in the power of
laser radiation, at some point they reach such a limit that there is not enough energy to further increase the concentration. And accordingly, the concentration of particles begins to fall, and decreases the intensity of the spectral lines.

Figure 5. Graph of dependence of the relative intensity of spectral lines on the pressure in argon

Figure 6 shows the dependence of the average power of laser radiation after the formation of the plasma channel on the pressure values. In the initial phase, the capacity sharply decreases as the particle concentration increases, and, accordingly, this requires energy. Then comes the so-called effect of «saturation» when the concentration of particles has reached a certain value, and for further increase requires more energy. But the power of laser radiation remains unchanged. Also, laser energy can go to various processes occurring in the plasma, for example, dissipate, go to increase the luminosity of the channels.

Figure 6. Dependence of the power of laser radiation passing through the plasma channel on the pressure
Figure 7 shows a graph of the dependence of the electron temperature of the plasma on the pressure.

![Graph of the dependence of the electron temperature of the plasma on pressure](image)

Figure 7. A graph of the dependence of the electron temperature of the plasma on pressure

4. Conclusion
Spectral diagnostics occupies a special place among many methods of plasma research, as it provides non-contact and fast measurements. In this paper, the electron temperature of laser-induced plasma channels in argon at different pressures was determined by the method of relative intensity of spectral lines. The length of the formed plasma channels was also measured.

References
[1] Bernhardt J, Liu W, Théberge F, Xu H L, Daigle J F, Châteauneuf M, Chin S L, 2008 Optics Communications 5 (281) 1268–1274
[2] Liu W, Bernhardt J, Théberge F, Chin S L, Châteauneuf M, Dubois J, 2007 Journal of Applied Physics 3 (102) 033111
[3] Tarasova M A, Khorkov K S, Kochuev D A et al. 2018 Bulletin of the Lebedev Physics Institute 45 (8) 246–250
[4] Tarasova M, Khorkov K, Kochuev D, Prokoshev V, Ivaschenko A, 2019 Journal of Physics: Conf. Series 1238 012031
[5] Kandidov V P, Shlenov S A, Silaeva E P, Dergachev A A, 2010 Optics of the atmosphere and ocean 23 (10) 873-884