Definition of brightness temperature and restoration of true temperature of laser-induced plasma channel in nitrogen at different pressures

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Abstract. In this paper we study the properties of laser-induced plasma channels formed by femtosecond laser radiation in nitrogen. The temperature of the plasma channels was measured using a color pyrometer that measures the brightness temperature.

1. Introduction

Measurement of brightness temperature is possible using a pyrometer. Photopyrometry method belongs to the group of temperature measurement methods [1]. Measuring the intensity of thermal radiation or absorption of radiation is the basis of all optical methods. Object temperature is an important factor in this method, it has a strong influence on the intensity of thermal radiation. For example, with decreasing temperature, the intensity of thermal radiation decreases sharply. Pyrometry methods are generally more expedient to use for measuring high temperatures. At temperatures below 1000 °C, pyrometry methods do not play a dominant role, but at temperatures above 1000 °C they become the main ones, and at temperatures above 3000 °C they are practically the only methods for measuring temperature. The advantage of using pyrometry methods is that this method belongs to the group of non-contact measurements. In this case, no direct contact of the measuring device with the object to be measured is required [2]. Due to this, pyrometry method is applicable for measuring high temperatures. When using the method of pyrometry, it is necessary to take into account several conditions, namely, the radiation of the object must obey the Kirchhoff radiation law, to be purely thermal [3]. Liquids and solids are usually satisfied with this requirement at high temperatures. In the case of gas use or plasma formation, clarification of physical conditions is required. Plasma radiation, provided that the velocity distribution of atoms, molecules and ions of the plasma corresponds to the Maxwell distribution, obeys Kirchhoff’s law. The populations of the excited energy levels should correspond to the Boltzmann law, and dissociation and ionization should be determined by the current law of masses. Under these conditions, the plasma becomes thermally equilibrium.

2. Experimental setup

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 was 1.5 W; pulse power density \( \sim 10^{13} \)
Many works are devoted to the study of laser plasma produced by femtosecond laser radiation [4-6].

When measuring the temperature of laser-induced plasma in nitrogen at different pressures, a color micro-pyrometer model MP-1001 was used. This device allows you to measure the brightness temperature in the range from 1500 to 5000 K. The transition from brightness temperature ($T_{br}$) to actual ($T_{act}$) is carried out in accordance with the formula [3]:

$$T_{act} = \frac{T_{br} C_2}{C_2 + \lambda T_{br} \ln(\alpha)}$$  \hspace{1cm} (1)

where $\lambda = 650$ nm is the reference/calibrated pyrometer wavelength $C_2 = 0.014388$ m·K, the second Planck constant, $\alpha$ is the degree of blackness (absorption coefficient). The degree of blackness was determined by measuring the intensity of a transmitted reference/probe laser beam with a wavelength of 650 nm through the volume of a laser-induced plasma channel. The scheme of the experimental setup is shown in figure 1.

![Figure 1. Scheme of the experiment setup: 1 – femtosecond laser system; 2 – focusing lens; 3 – insulated vessel; 4 – area of optical breakdown and formation of a plasma channel; 5 – input and output windows in an isolated vessel.](image)

The laser radiation was focused by a single plane-convex lens with a focal length of 150 mm into the vessel, allowing the study of laser-induced processes in various media at different pressures and temperatures. Since to calculate the true temperature it was necessary to know the degree of plasma absorption, a scheme was developed for measuring this coefficient. The scheme is shown in figure 2.
Figure 2. The scheme of the experiment. 1 – laser radiation; 2 – focusing lens; 3 – insulated vessel; 4 – area of optical breakdown and formation of a plasma channel; 5 – input and output windows in an isolated vessel; 6 – collimator; 7 – beam splitting cube (50%).

The image of the experimental scheme in the laboratory is clearly demonstrated in figure 3.

Figure 3. Experimental scheme: 1 – power sensor photodetector; 2 – insulated vessel; 3 – CCD camera; 4 – laser radiation of the main laser; 5 – gas supply to the vessel; 6 – pilot laser.

The scheme made it possible to measure the degree of absorption of laser radiation by the plasma. The laser radiation from the pilot semiconductor laser was focused by a plane-convex lens with a focal length of 150 mm in the region of the laser-induced plasma, then it fell on the measuring head of the
photodetector. Thus, the power values were recorded when the main femtosecond radiation passes through the laser plasma together with the radiation of the pilot laser, and the power values when only the radiation of the pilot laser passes. At different pressures, the position of the plasma channel changes, probably due to density fluctuations that occur inside an isolated vessel. When measuring the absorption coefficient, the important point is that the radiation of the pilot laser passes strictly through the plasma channel, for this purpose the pilot laser was fixed on a precision three-coordinate table, which allowed it to be moved.

3. Results
During the experiment to measure the degree of absorption of plasma, the absorption coefficient was calculated. The values of plasma absorption coefficient as a percentage of the pressure value are presented in figure 4.

![Figure 4. Graph of the absorption coefficient of the plasma pressure.](image1)

The pyrometer measured the brightness temperature of the plasma, the transition to the actual temperature occurred in accordance with the formula (1). The brightness temperature values are shown in figure 5.

![Figure 5. Graph of the brightness temperature of the plasma from the pressure.](image2)

Figure 6 shows a graph of the actual temperature versus pressure values.
Also during the work the dynamics of formation of plasma channels was monitored, their length were measured. Figure 7 shows a graph of the dependence of the length of the plasma channel on the pressure values.

Figure 8 shows images of the plasma channel at different pressures. We can say that up to a certain point the length and luminosity of the plasma channel increases.
4. Conclusion
An experimental scheme was developed to measure the temperature of laser-induced plasma channels using a pyrometer at different pressures. A scheme for measuring the plasma absorption coefficient has also been developed. The temperature values of plasma channels are obtained, the dynamics of formation of plasma channels is studied, namely, the length is measured and the images of plasma channels are obtained.

References
[1] Nesteruk D A, Vavilov V P 2007 Thermal control and diagnostics. – (Tomsk: Tomsk Polytechnic University) p 104
[2] Dubas L G, 2018 Bulletin of Moscow State Regional University. Series: Physics and Mathematics 3 54-64
[3] Magunov A N, 2010 Scientific Instrument Engineering 20 (3) 22–26
[4] Tarasova M A, Khorkov K S, Kochuev D A et al. 2018 Bulletin of the Lebedev Physics Institute 45 (8) 246–250
[5] Tarasova M, Khorkov K, Kochuev D, Prokoshev V, Ivaschenko A, 2019 Journal of Physics: Conf. Series 1238 012031
[6] Chekalin S V, Kandidov V P, 2013 Successes of physical sciences 183 (2) 133-152