Peculiarities of plasma formation in a pulse of a cesium pulsed-periodic discharge

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The paper presents the results of spectroscopic measurements in a pulsed-periodic discharge in cesium vapor. The spectra of the recombination continuum were recorded at different times of the linearly increasing current pulse (with a resolution of 1 μs) and in decay. This made it possible to determine the plasma parameters: concentration and temperature.

Keywords: gas discharge, cesium, recombination continuum, plasma density and temperature.

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The emission from cesium high-current pulsed-periodic discharge (PPD) lighting lamps is formed mainly due to 6P- and 5D-recombination continua. In optimal luminosity modes, the discharge plasma is optically quite dense in the head of the 6P-continuum and radially inhomogeneous. Nevertheless, in [1] it was shown that for the 5 mm-diameter discharge tubes (burners) studied by us, the recombination continuum radiation allows us to determine the temperature of T electrons and the concentration of n_e plasma electrons in the near-axis central region of the discharge in the entire region of working pressures of cesium vapor without large error. Note that in a plasma with single-charged ions $n_e = n_i = n$, where n_i — the ion concentration, n — the plasma concentration. The aim of the present work is to diagnose the plasma of cesium PPD by recombination continuum.

The design of the lamps on which the research was carried out and the method of measurement are described in [1]. The pressure in the burner was set by its cold point temperature, and xenon with a pressure of 40 Torr was used to ignite the cold bulb. The inner diameter of the monocrystalline sapphire burner was 5 mm, the interelectrode spacing was 22 mm, and the diameter of the twisted tungsten electrodes was 2 mm. The lamp was powered from a current generator by pulses of alternating polarity with a linearly increasing current of duration 20–50 μs with fast (2–3 μs) interruption. Spectroscopic measurements were performed on an MDR-23 monochromator using the gated integration method with a time resolution of $\sim 1\,\mu$s. Photomultiplier FEU-79 was used as a radiation receiver.

Figure 1 shows a series of spectra recorded for a wide range of lamp powers and, respectively, cesium vapor pressures p_{Cs} at the same current pulse with amplitude $I_m = 60$ A and duration $\tau = 30\,\mu$s. The increase in the average electrical power P, invested in the discharge, was realized by increasing the pulse repetition rate f. At increasing power (and pressure), the reabsorption of the continuum becomes strong, leading even to a decrease in its integral emission starting at about 200 W (see, e.g., spectrum *5*, pressure estimate ~ 1 atm).

The measurements showed that at a power of 90 W, intensity dips appear in the spectra in the 390–405 and 450–520 nm bands, which increase with increasing discharge power (cesium pressure). These dips are caused by the absorption by of Cs_2 molecules. It is known that equilibrium cesium vapors contain besides Cs atoms also molecules Cs_2, and with increasing pressure the relative fraction of molecules grows and at a pressure of 30 Torr is 2%, and at 1 atm — 6% [2]. As the temperature increases at constant pressure, the concentration of Cs_2 molecules decreases, so in a cesium lamp the Cs_2 molecules are concentrated in a relatively cold (temperature ~ 1000 K) narrow near-wall zone. Therefore, when radiation passes through the cold near-wall zone, dips in place of molecular

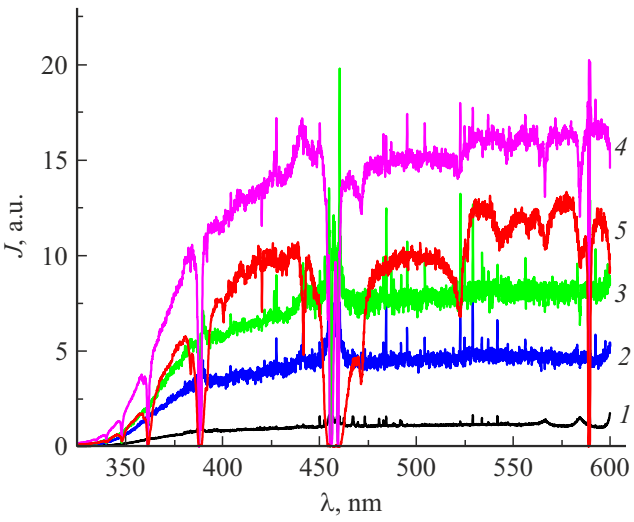

Figure 1. Discharge spectra with a maximum current of 60 A at varying average power. P, W: *1* — 20, *2* — 44, *3* — 67, *4* — 107, *5* — 324 (cesium pressure from ~ 10 Torr to ~ 1 atm). λ — wavelength. The spectra were recorded at the end of the pulse.

bands appear in the continuum spectrum. The reduction in integrated emission caused by molecular absorption depends on the mode of operation of the lamp and can be up to 20%. Such significant absorption affects even the luminous efficacy of the lamp, and even more so it must be taken into account when diagnosing the lamp from the recombination continuum. The absorption spectra of Cs_2 have been investigated for a long time. Very detailed data on molecular transitions have been obtained to date (see, for example, [3,4]).

In the [5] model, the dependence of $\ln(I_\lambda \lambda^3)$ on $1/\lambda$ is a straight line, from whose slope the electron temperature T is determined. Note that in the case of high pressure (more than 50 Torr) and large plasma concentration, the temperatures of electrons, ions, and atoms practically coincide in most of the burner. Only in a very narrow near-wall region the electron temperature detachment is observed. In the case of molecular absorption, there are deviations from a straight line at the sites of molecular bands. Naturally, these areas should not be taken into account when drawing a straight line and determining its slope. To determine the $T(t)$ dependence, a long-term recording of 10–15 spectra of the 6P- continuum in the wavelength range shorter 520 nm [1] at various time points in the pulse and plasma decay is required. One can greatly simplify the measurements by recording the time dependences of the continuum emission J_λ at two wavelengths λ_1 and λ_2 from the specified range. Obviously, there should be no atomic lines and no molecular absorption on λ_1 and λ_2.

Figure 2, *b* shows the time dependence of temperature calculated from the curves presented in Figure 2, *a* and for two other modes, where the modes *2* and *3* in Figure 2, *b* correspond to the end of the current pulse 50 μs, and the mode *1* — 40 μs. It can be seen from the figure that the error in determining T is $\pm$300 K. The systematic error associated with the radial dependence T, does not exceed 5–10% [1].

Calibration of the sensitivity of the registration system using a reference band lamp made it possible to obtain absolute values of the $J_\lambda(t)$ continuum intensity and to calculate from them the dependence of the concentration on time. A typical result for the $n(t)$ dependence is shown in Fig. 3 for a regime close to the *3* regime in Fig. 2, *b*. The error in the concentration determination is determined by the radial dependence T and by some scatter in the photorecombination cross section in different works. By our estimates this error is $\pm$50%.

Figure 2,*b* shows that the change in electron temperature along the pulse depends significantly on the discharge mode. At large pressures (modes *2, 3*), the electron temperature increases rapidly at the beginning of the pulse (in the first 5–7 μs), and in the rest of its part, when, in fact, a dense plasma is formed, it changes insignificantly, in some modes even decreasing before the current interruption.

For the low-power, low-pressure ($\sim$ 10 Torr) *1* mode with a distributed discharge, the character of the temperature

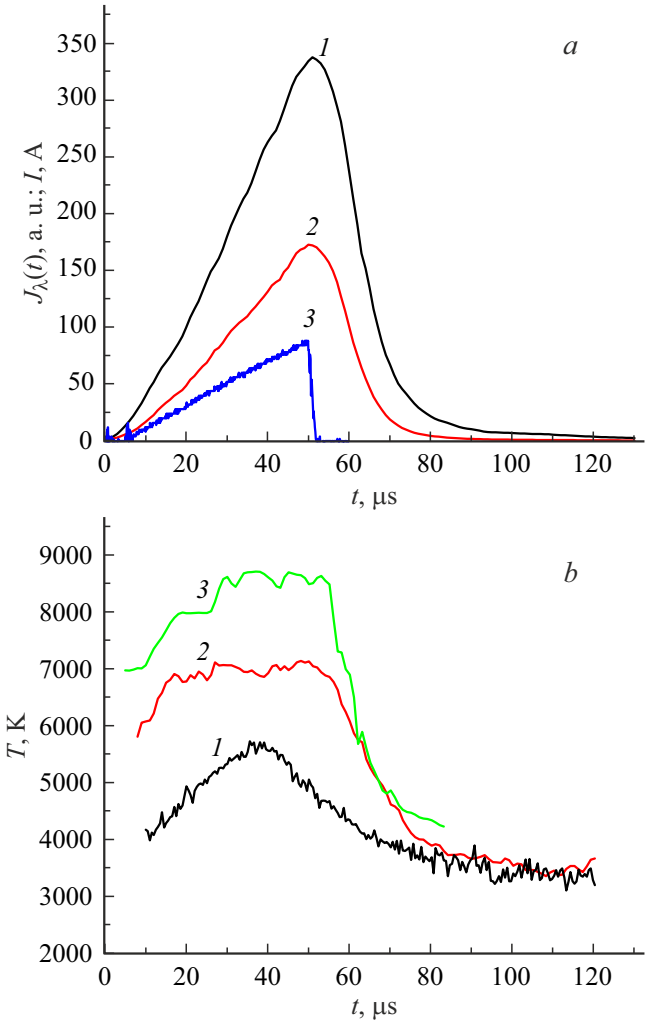

Figure 2. *a* — the time dependencies of $J_\lambda(t)$ at wavelengths $\lambda = 531$ (*1*) and 410 nm (*2*) and current I (*3*) for power 105 W; *b* — the time dependencies of $T(t)$ for power $P = 14$ (*1*), 105 (*2*), 92 W (*3*).

variation along the pulse is quite different: the temperature grows almost uniformly throughout the pulse.

But at the decay stage, after cessation of energy supply to the discharge plasma, its temperature for all modes changes equally. First, there is a rapid (in a time of about 30 μs) decrease in temperature to 4000–3500 K (Fig. 2, *b*). Since the local thermodynamic equilibrium [6] must obviously be fulfilled in the conditions under consideration, the concentration falls as fast (Fig. 3). After this, the rate of decrease of T and n decreases. It can be assumed that the initial rapid cooling of the plasma is mainly due to the output of recombination radiation. The temperature change almost ceases when the radiation intensity drops by two orders of magnitude. It can be seen from Fig. 3 that the concentration in the long-range decay changes slowly, so that by the start of the next pulse it remains at least 10^{14} cm^{-3}. This well explains the rapid development of the discharge in each pulse in the absence of a low-current standby discharge.

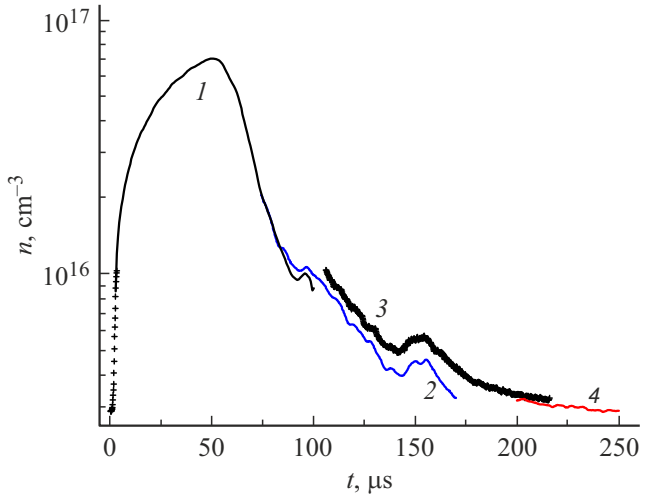

Figure 3. Time dependence of plasma concentration in the IPR for $I_m = 85$ A, $f = 515$ Hz, $P = 75$ W. The *1–4* sections of this curve were obtained at different monochromator slit widths.

The characteristic long-range decay times (1–3 ms) are not inconsistent with estimates of the ambipolar diffusion time (0.01–0.1 s). The final conclusion of such a high residual concentration needs further investigation.

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Conflict of interest

The authors declare that they have no conflict of interest.

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