

Effect of radiation refraction on the characteristics of a cw optical discharge

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Abstract. One-dimensional model of a continuous optical discharge is proposed, allowing the estimation of its parameters in a converging laser beam taking into account the refraction of the radiation on the discharge. The influence of spherical aberrations of a focusing lens on the measured thresholds of maintenance of the discharge in the laser plasmatron mode has been discussed.

1. Introduction

The continuous optical discharge supported by a CO₂-laser radiation was extensively studied in the last quarter of last century. At the present time, these studies are continued at the new stage [1] when a possibility was shown of effective synthesis of diamond coating using a continuous optical discharge in the laser plasmatron mode [2]. One of the main characteristic of an optical discharge in this mode is the threshold power of laser radiation that is necessary to maintain the discharge in the dependence on the gas flow rate. It was shown in the experiments [3] that this dependence has a minimum for long-focusing lenses and is characterized by monotonic decrease in the power as the gas flow rate decreases up to zero as short-focus lenses are used. The numerical calculations [4] confirmed these features and for discharge in Ar under atmospheric pressure made it is possible to find a conventional boundary between long-focus and short-focus lenses with respect to the value of the half-angle of focusing the radiation in the vicinity of $\varphi \approx 0.125$ rad.

The optical discharge plasma is characterized by large transverse gradients of the electron density and the gas density and, because of this, can cause the radiation refraction on the discharge. A qualitative indication of the existence of noticeable laser beam refraction on an optical discharge is presented in [5]. Authors [6] experimentally proved for the first time the possibility of refraction broadening of a laser beam on the optical discharge plasma that was supported by this laser beam. The value of the broadening was estimated in recent work [7] and corresponds to the experimental data [6]. Some of the experimentally observed features of discharge burning in a laser beam at the weak focusing [8] are also related with the radiation refraction.

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The results of experimental and theoretical studies devoted to determination of the discharge boundaries in a convergent laser beam depending on the conditions of its maintenance are presented in [9-12].

The aim of this work is to study the influence of the radiation refraction and the lens spherical aberrations on the boundaries position and the conditions of maintenance of a continuous optical discharge.

2. Focusing of radiation

Figure 1 shows the scheme of radiation focusing. Here r_0 is the radius of the focused laser beam, P is the laser radiation power, v_0 is the gas flow rate, r_1 , r_2 are radii of the front and back discharge boundaries, z_1 , z_2 are the coordinates of the discharge boundaries at the optical axis, φ_p is the radiation refraction angle, r_f is the focal spot radius, $\varphi = (r_0 - r_f)/f$ is the angle of radiation focusing (here f is the lens focal length).

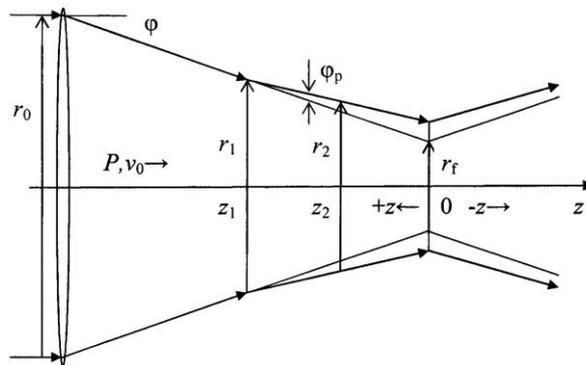


Figure 1. Scheme of radiation focusing.

Taking into account the lens spherical aberrations, focal spot radius r_f is

$$r_f = \frac{a(2r_0)^3}{f^2} + \gamma_0 f, \quad (1)$$

here $r_0 = rH$ and $\gamma_0 = \gamma/H$ is the beam radius and the radiation divergence after telescoping the beam exited from the laser, r and γ are the radius and the divergence in the laser output, H is the telescope magnification. For convex-flat cylvite lenses used in the experiments and in calculations, coefficient $a = 0.044$, the values $r = 10$ mm and $\gamma = 3.5 \cdot 10^{-4}$ rad correspond to the parameters of the laser used.

Figure 2 presents the dependences r_f on f calculated by formula (1) at $H = 1, 1.5$ and 2 . At constant f , radius r_f can both increase and decrease with increasing H . The position of the minimum in the dependences shown in figure 2 corresponds to focal length f_{opt} and spot radius r_{fmin} calculated by formulas $f_{opt} = (2a/\gamma_0)^{1/3} 2r_0$ and $r_{fmin} = 1.5f_{opt}\gamma_0$.

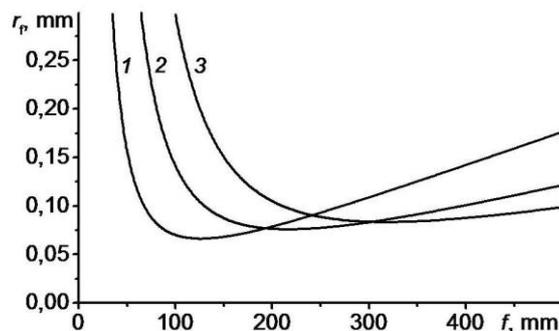


Figure 2. Dependences r_f on f for $H = 1$ (1), 1.5 (2) and 2 (3).

3. Model of discharge and calculation results

In a paraxial approximation, coordinates z_1 and z_2 are (see figure 1)

$$z_1 = \frac{r_1 - r_f}{\varphi}, \quad (2)$$

$$z_2 = \frac{r_2 - r_f - z_1 \varphi_p}{\varphi - \varphi_p}. \quad (3)$$

In a stationary discharge, the radiation intensity at the back boundary must be equal to the intensity at the front boundary. Based on this, we take into account the increase in the intensity at the back boundary due to the beam compression and simultaneously its decrease because of radiation absorption. From the obtained balance relationship, we find

$$r_2 = \frac{r_1}{[1 + \exp(-\alpha(z_1 - z_2))]^{1/2}}, \quad (4)$$

where α is the radiation absorption coefficient.

The angle of radiation refraction we find using the equation of a light beam in the paraxial approximation

$$\frac{d}{dz} \left(N_p \frac{dr}{dz} \right) = \nabla N_p, \quad (5)$$

where $N_p = \beta N_e + (1 - \beta) N_g$ is the discharge refractive index, r is the transverse coordinate, $\beta = [n_e T / (n_0 T_0)]$ is the degree of gas ionization, N_e and N_g are the refractive indexes of the electron and gas components, T is the discharge temperature, n_e is the electron density, n_0 is the normal gas density, $T_0 = 300$ K. Neglecting the dependence of N_p on z and taking into account $N_g \approx 1$, $N_e \approx 1$ and replacing δr for $(r_1 + r_2)/2$, we obtain for $\varphi_p = dr/dz$

$$\varphi_p = \frac{[\beta |\delta N_e| + (1 - \beta) |\delta N_g|] (z_1 - z_2)}{0.5(r_1 + r_2)}, \quad (6)$$

here $|\delta N_e| \approx n_e / 2n_{ec}$, $n_{ec} \approx 1.2 \cdot 10^{19} \text{ cm}^{-3}$ is the critical electron density for CO₂-laser, $|\delta N_g| = (N_{g0} - 1)(1 - T_0/T)$, N_{g0} is the refractive index of the gas at normal conditions.

Now we will use the expression from [13] for the propagation velocity v_0 of thin optical discharge in laser beam through a cold gas

$$v_0 = \frac{1}{c\rho_0} \left(\frac{k\alpha}{T} \right)^{1/2} \left(I - \frac{\Phi}{\alpha} - \frac{\eta kT}{\alpha R^2} \right)^{1/2}, \quad (7)$$

here c is the specific heat capacity, k is the thermal conductivity coefficient, and Φ is the specific radiation loss power. Term $\eta kT/\alpha R^2$ approximately describes the lateral losses of a discharge with radius R for thermal conduction, $\eta = 2$. At $v_0 = 0$, it follows from (7) that the threshold intensity at the discharge front is

$$I_t = \frac{\Phi}{\alpha} + \frac{\eta kT}{\alpha R^2}. \quad (8)$$

Let expression (8) is also valid for the discharge with a finite thickness. Then, taking into account $R = (r_1 + r_2)/2$, we find the radius for the front discharge boundary

$$r_1 = \left(\frac{0.86P}{\pi I_t} \right)^{1/2} = \left(\frac{0.86P}{\pi \left(\frac{\Phi}{\alpha} + \frac{4\eta kT}{\alpha(r_1 + r_2)^2} \right)} \right)^{1/2}, \quad (9)$$

here factor 0.86 reflects the fraction of the total power P in the laser beam.

Equations (2)-(4), (6) and (9) form a system of equations from which we can find r_1 , r_2 , z_1 , z_2 , φ_p using known Φ , α , n_e and T .

The calculation were performed for Ar at pressure $p=1$ atm. The values Φ , α , n_e as functions of T were calculated using the formulas from the monograph [14]. The thermal conductivity coefficient of Ar was linearly extrapolated with respect to temperature using the data [15]. This system of equations is valid for short-focus lenses, when the discharge is localized in the beam and exists in a steady state at $v_0=0$. Under these conditions, the measurement results [9] can be used, according to which the discharge temperature in Ar at $p=1$ atm and $v_0=0$ is 17 kK and it is independent on P .

Figure 3 shows the calculated dependences of z_1 , z_2 , φ_p on P for the short-focus lens with $f=130$ mm ($H=2.06$, $\varphi\approx 0.16$ rad); the dashed line shows the calculations for $\varphi_p=0$. The power varies in the range beyond of which discharge does not exist because of violation of the condition of the intensity equality at the boundaries. For the chosen lens, the relative decrease in z_2 caused by the radiation refraction is insignificant, since inequality $\varphi_p \ll \varphi$ is fulfilled over entire range of the power change.

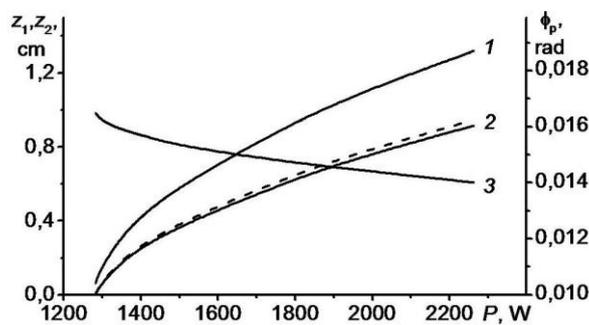


Figure 3. Calculated dependences of z_1 (1), z_2 (2), φ_p (3) on P for $f=130$ mm. Ar, $p=1$ atm, $v_0=0$, $T=17$ kK. Dashed line is the calculation for $\varphi_p=0$.

This model allows one to calculate, for short-focus lenses, the radii, the boundary coordinates and the refraction angle also for the discharge in the laser plasmatron mode. In this mode, as v_0 increases, the discharge shifts to the focal plane, and the radiation intensity I_1 at its front boundary increases according to the expression

$$I_1 = I_{10} + (v_0 c \rho_0)^2 \frac{T}{k\alpha}. \quad (10)$$

At given value of v_0 , the intensity I_1 is a known value, since the expression contains the known intensity $I_{10}=0.86P/(\pi r_{10}^2)$ at the known radius r_{10} calculated for $v_0=0$. Because of this, the values r_1 and z_1 are also known at $v_0 \neq 0$ and are determined by formula $r_1=[0.86P/(\pi I_1)]^{1/2}$ and by equation (2). As a result, the number of unknown parameters decreases to three (r_2 , z_2 , φ_p), and these parameters can be found by solution of the system consisting of equations (3), (4), (6).

Figure 4 shows the results of calculations of the threshold power P_{th} in dependence on v_0 for short-focus lenses with $f=100$ mm (curves 1, $\varphi\approx 0.21$ rad) and $f=130$ mm (curves 2, $\varphi\approx 0.16$ rad) and the same $H=2.06$ at $\varphi_p \neq 0$ (solid curves) and $\varphi_p=0$ (dashed curves). Insignificant increase in the discharge temperature with v_0 [4] was neglected, and its value used in the calculations was 17 kK. The threshold power P_{th} was found for $z_2 > 0$ near the focal plane, although this model allows one to calculate also a negative value of z_2 behind the focal plane. However, at $z_2 < 0$, the balance of the intensities at the boundaries is violated fast, and the choice of near-zero positive values of z_2 provided adequate accuracy of the calculations. It is seen from figure 4 that the inclusion of the refraction for v_0 at the right of the characteristic kink in the dependences presented leads to the increase in P_{th} as compared to the case $\varphi_p=0$, and this increase becomes more significant with increasing f . We can't to confirm such behaviour of P_{th} on v_0 in our conditions due to the features of the plasmatron construction not allowing to use the short-focus lenses.

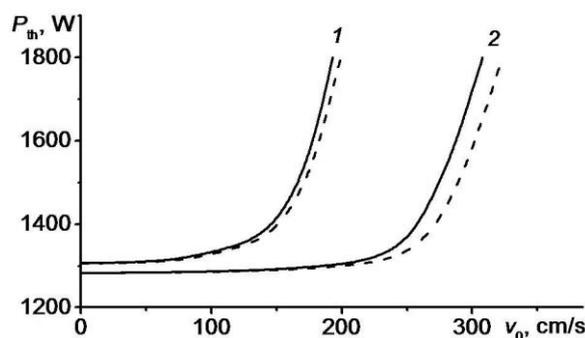


Figure 4. Calculated dependences of P_{th} on v_0 for $f=100$ (1) and 130 mm (2) at $\phi_p \neq 0$ (solid lines) and $\phi_p = 0$ (dashed lines). Ar, $p=1$ atm, $T=17$ kK.

4. Measurement of the threshold power

A comparison of the values of P_{th} in figure 4 for both lenses at $v_0 \sim 100$ cm/s shows that P_{th} for the lens with $f=100$ mm is higher. It can be a result of the fact that radius $r_f=0.32$ mm at $f=100$ mm is noticeably larger than $r_f=0.2$ mm at $f=130$ mm (figure 2). Because the increase in the flow rate fast shifts the discharge to a near-focal region, the threshold power for the lens with smaller focal length must increase to provide the unchanged threshold radiation intensity at the discharge front. This conclusion does not reflect increasing difference between the calculated values of the threshold power with the increase in the flow rate related to the necessity of fulfilling the intensity balance at the discharge boundaries. Based on this conclusion, let us compare the results of measuring the threshold power for two long-focus lenses shown in figure 5. The lens with $f=170$ mm has a smaller radius r_f , since its focal length, as well as the focal length of the lens with $f=152$ mm belong to the descending branch of dependence r_f on f in figure 2. Because of this, the threshold power for the lens with $f=170$ mm must be lower.

As was noted above, the existence of the minimum in dependence of P_{th} on v_0 is typical of long-focus lenses when the discharge decays at $v_0=0$. The model under consideration does not describe the appearance of the minimum, since P_{th} is calculated using the results of the calculations for $v_0=0$.

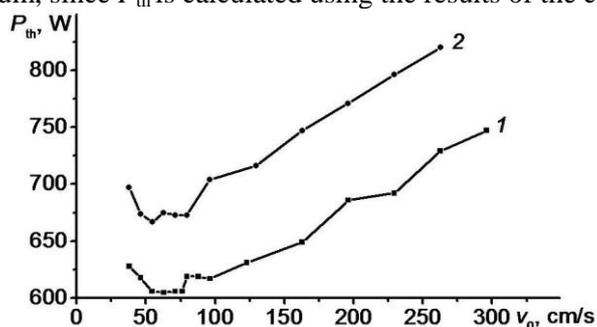


Figure 5. Measured dependences of P_{th} on v_0 for Ar at $p=1$ atm, $f=170$ (1) and 152 mm (2), $H=2.06$.

5. Conclusions

In this work it was shown that the radiation refraction on the optical discharge noticeably influences the threshold power depending on the gas flow rate as short-focus lenses were used near the boundary of transition to long-focus lenses; the criteria for the short-focus lenses were chosen on the base of previous studies. Spherical aberrations of lenses can also strongly affect the threshold power.

Acknowledgments

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