Radiative losses by argon plasma and the emissive model of a continuous optical discharge

G. I. Kozlov, V. A. Kuznetsov, and V. A. Masyukov

Institute of Problems in Mechanics, USSR Academy of Sciences
(Submitted September 28, 1973)
Zh. Eksp. Teor. Fiz. 66, 954–964 (March 1974)

The properties of a continuous optical discharge are explained in terms of an analysis of the radiative balance which is established at high pressures between the absorption of the laser radiation and the emission of the discharge integrated over the entire spectrum. The resulting formula for the radiation losses by dense plasma is confirmed by experimental data on the continuous optical discharge in argon.

A continuous optical discharge (COD) in a focused laser beam was obtained for the first time quite recently.[1,2] Published literature on COD suggests that there is considerable interest in this new type of continuous discharge.[3-5] Our main aim was to elucidate some of the more important properties of COD which were described in a previous paper.[2] In particular, there is considerable interest in the nature of the so-called upper limit for the existence of COD which restricts the power that can be introduced into the discharge and, consequently, the temperature and brightness.

It will be shown below that, at high pressures, radiative COD losses dominate all other losses. It may therefore be supposed that, under the above conditions, the properties of COD are determined by the radiation balance between the absorption of laser radiation and the emission of the discharge integrated over the spectrum. However, a detailed analysis of this balance on the basis of existing data on radiation losses was found to be very difficult mainly because of the absence of an analytic expression for the integrated emissive power of dense plasma and the considerable disagreement between different experimental data.

We have therefore undertaken an attempt to fill this gap. Analysis carried out in the spirit of the paper by Biberman and Norman[6] has led us to a simple approximate formula which does, nevertheless, provide a good description of experimental data on the integrated emissive power of plasma, which we have obtained for COD.

We have used this formula to analyze the radiation balance and to develop an emissive model of COD. This model provides a clear qualitative explanation of the properties of COD described previously. Our analysis was carried out for argon but its results are of more general significance.

1. RADIATIVE LOSSES OF DENSE PLASMA

Estimates show that under the conditions in which we are interested ($p > 5$ atm), the COD plasma completely reabsorbs radiation due to transitions to the ground state. It will be shown below that the discharge plasma is transparent to the remainder of the radiation. It follows that the quantity which determines the radiation losses by this plasma is the emissive power due to free-free transitions (bremsstrahlung), free-bound transitions to various excited states (recombinational emission), and discrete transitions between excited states of the atom or ion (line emission).

The starting point of our analysis is the well-known Biberman-Norman formula for the spectral emissive power in the continuum in the region of first ionization:[6]

$$\varepsilon_\nu{}^c = 5.44\cdot 10^{-39}\frac{N_e N_+}{T^{1/2}}\exp\left(-\frac{\Delta I}{kT}\right)\xi(\nu) \times \begin{cases}\exp(h\Delta\nu/kT), & \nu\leqslant\nu_g-\Delta\nu\\ \exp[h(\nu_g-\nu)/kT], & \nu\geqslant\nu_g-\Delta\nu\end{cases}. \qquad (1)$$

Here and below, we use standard notation, and the numerical factors are given in cgs units. In the above formula, ΔI is the reduction in the ionization potential which can be calculated, for example, from the Ecker-Kröll formula[7] $\Delta I = 1.4e^2/\rho_D$, where ρ_D is the Debye radius, $\xi(\nu)$ is a factor of the order of unity, which is not very dependent on temperature and takes into account the structure of the atomic terms, and ν_g is the limiting frequency which is equal to the maximum photoelectric threshold frequency for the levels taken into account in the integrated expression. For argon, it may be supposed that all the terms, other than the 4s levels, form a continuous sequence, and are therefore taken into account in the integration ($\nu_g = 2.85$ eV). The contribution of the 4s levels will be neglected for the moment.

The formula given by (1) allows for recombination and bremsstrahlung radiation. All that remains is to take into account the line spectrum. In point of fact, some of this radiation is already included in (1) through the factor $\exp(h\Delta\nu/kT)$. These are the transitions from levels near the ionization limit which, as a result of Stark broadening, form the so-called pseudocontinuum. The quantity $h\Delta\nu$, which is the expression for the depression of the continuous spectrum limit, is equal to the binding energy in the last distinguishable level. The fact that the set of lines can be represented by the single factor $\exp(h\Delta\nu/kT)$ is due to the fact that the spreading of the absorption cross section over the spectrum for the higher terms of the series passes continuously into the photoelectric cross section (this is the principle of spectroscopic stability).

The basic principle, whereby the contribution of the entire line spectrum to the spectral emissive power is approximately taken into account, is to extend this principle to all the levels in the continuous sequence of terms. Formally, this means that in (1) we can substitute $\Delta\nu = \nu_g$, in which case, the spectral emissive power of plasma with "smeared out" lines is given by

$$\varepsilon_\nu = 5.44\cdot 10^{-39}\frac{N_e N_+}{T^{1/2}}e^{-\Delta I/kT}\xi(\nu)\exp\left[\frac{h(\nu_g-\nu)}{kT}\right]. \qquad (2)$$

In point of fact, experiment shows that transitions from levels lying below $h\Delta\nu$ appear in the form of discrete lines. However, since we are interested in the emission of optically thin plasma, integrated over the spectrum, this fact has very little significance. Integration of (2) over the spectrum gives the following expression for the emissive power of plasma in the region of first ionization:

$$\varepsilon_s = \int_0^\infty \varepsilon_\nu \, d\nu = 1.14\cdot 10^{-26} N_e N_+ \left(\frac{T}{10^4}\right)^{1/2} \exp\left(\frac{h\nu_g - \Delta I}{kT}\right). \quad (3)$$

Since the formulas are approximate, and $\xi(\nu) = 1$ for small ν, we have set

$$\int_0^\infty \xi(\nu) e^{-h\nu/kT} d\nu = \frac{kT}{h}. \quad (4)$$

The formula given by (3) does not include the contribution due to the 4s levels which, according to Yakubov,[8] is an appreciable quantity of the order of 30%. However, fortunately, calculations show that this is almost completely compensated by the overestimate in (2) of the emission in the region of small quanta. This overestimate is due to the fact that, near ν_g, transitions with small quantum energies are impossible because the levels in this region belong to the single 4p group which is, in fact, isolated from the higher-lying terms with a gap of 1 eV.

Equation (3) is readily generalized to the case of higher temperatures. For example, when second ionization is taken into account, we have

$$\varepsilon_s = 1.14\cdot 10^{-26} (T/10^4)^{1/2} e^{-\Delta I/kT} N_e [N_+ \exp(h\nu_g/kT) + Z^2 N_{++} \exp(h\nu_g^+/kT)], \quad (5)$$

where ν_g^+ is the end-point frequency of the ion. In the case of the argon plasma, this formula also contains an overestimate of the contribution of the long-wave line spectrum of both atoms and (for analogous reasons) ions. However, for ions, the above atuomatic compensation of the overestimate does not occur because of the absence of isolated low-lying terms. It is not, as yet, possible to calculate or guess the effective limiting frequency using only the ion or atom terms. The best agreement with experimental data on the temperature dependence of the integrated emissive power of argon plasma is achieved when the effective value of the limiting frequency for the ion is assumed to be 8.2 eV (the true value of ν_g^+ is 11.2 eV).

The formula given by (5) leads to an important conclusion. Because of the factor $Z^2 = 4$ and the fact that ν_g^+ is much greater than ν_g, the contribution of ions to the integrated radiation is appreciable well before the second ionization becomes appreciable. It is precisely for this reason that the temperature dependence of ϵ_S has a non-decreasing character.

The above discussion of the derivation of (3) and (5), which give the integrated emissive power of plasma, and the values of ϵ_S calculated from them in the case of argon, are not distinguished by the necessary rigor from the standpoint of complete allowance for the structure of the atomic and ionic terms and, therefore, the only criterion for the validity of the results is their agreement with the experimental data.

Figure 1 shows the results of a calculation of the integrated emissive power of argon plasma and the experimental data reported by different workers. In the calculations, we used the Olsen data[11] on the equilibrium composition of argon plasma. Insofar as we know, there is only one paper[9] in which experimental

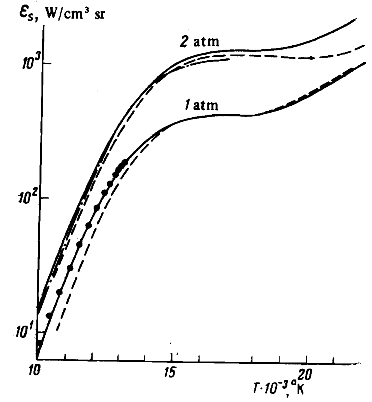

FIG. 1. Emissive power of optically thin plasma integrated over the spectrum (without allowing for radiation due to transitions to the ground state). Solid curves—calculations based on (5); dot-dash curve—experimental results of the present work; dashed curves—experiment; [9] points represent experimental results from [10].

data on ϵ_S are reported up to temperatures exceeding 20 000°K, when the line emission of ions becomes predominant. At pressures of 1 atm, these data are corrected for self-absorption (the dimensions of the plasma in the experiments described in[9] are quite substantial, i.e., about 5 cm) and, therefore, they may be used to determine the above values of ν_g^+. On the other hand, at pressures of 2 atm, Evans and Tankin[9] did not introduce this correction, and this may be the reason why the experimental data at high temperatures lie substantially lower than the calculated results. At low temperatures, on the other hand, the data obtained by Evans and Tankin[9] at 2 atm are in good agreement with calculations, and for 1 atm they are found to lie substantially lower. In this temperature region, the calculations are in good agreement both with the experimental data obtained in the present work and those reported by other workers, including the work of Krey and Morris,[10] which is the most recent and, in our view, the most reliable. This enables us to conclude that the low-temperature data of Evans and Tankin[9] at 1 atm are unsatisfactory. This is also confirmed by the fact that the data reported in[9] do not confirm the known fact that ϵ_S is proportional to pressure at low temperatures.

There is considerable interest in the contribution of the line emission to ϵ_S. Following the historical tradition,[12,13] we shall represent the contribution of the lines by the factor L which is defined by

$$\varepsilon_s = L \int_0^\infty \varepsilon_\nu^c \, d\nu. \quad (6)$$

Consider the line emission of the atom. From (1) and (3), we have

$$L = \exp[h(\nu_g - \Delta\nu)/kT][\xi(\nu_g - \Delta\nu) + \bar{\xi} h(\nu_g - \Delta\nu)/kT]^{-1}. \quad (7)$$

In this expression, $\bar{\xi}$ is the mean value of the ξ-factor. If the pseudocontinuum is bracketed together with the line emission, then in (7) we must set $\Delta\nu = 0$. In that case, it is readily seen that L depends only on temperature. As noted by Bauder,[13] the fact that L is independent of pressure is a very valuable feature. Thus, if we measure L at a given pressure, we use the continuous emission to find the integrated emission at any other pressure. Figure 2 shows the results of our calculations of L and the results obtained by other workers. It is clear from this figure that all the curves agree

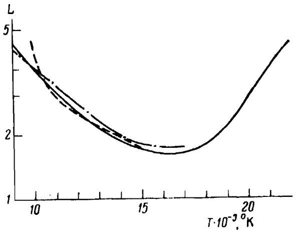

FIG. 2. Ratio of integrated emissive power to the emissive power in the continuum. The quantity L−1 is equal to the ratio of the line emission to the continuum. Solid curve—based on (7) [$\xi(\nu_g) = 2$; $\bar{\xi} = 1{\cdot}5$; $\xi(\nu_{g^+}) = \xi^+ = 1$; p = 1 atm]; dot-dash curve—calculated; [8] dashed curve—semiempirical data from [13].

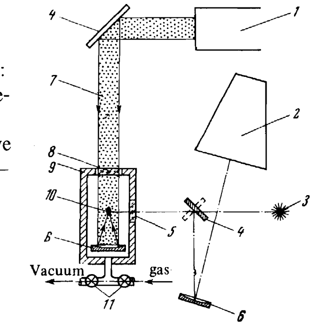

FIG. 3. Experimental arrangement: 1—powerful CO_2 laser; 2—recording device; 3—comparison source; 4—rotated mirror; 5, 8—NaCl windows; 6—concave mirror; 7—laser beam; 9—chamber; 10—COD; 11—valve.

with one another. At high temperatures, the calculations are based on a formula similar to (7) but in which second ionization is taken into account.

Figure 2 leads us to one important conclusion, namely, that the contribution of line emission to ϵ_S, especially at low and high temperatures, cannot be neglected. We are, of course, concerned with an optically thin volume of plasma.

The formula given by (2) enables us to estimate the maximum pressures at which the COD plasma can be regarded as transparent to integrated radiation. All that is required is to take into account the fact that the formula given by (3) overestimates the spectral intensity of the radiation in the infrared for the reasons indicated above. The corresponding correction ensures that ϵ_ν for argon has a maximum at $h\nu_m \approx 1$ eV. Using Kirchhoff's law together with (2), we can determine the absorption coefficient κ_m at frequency ν_m and the optical thickness $\kappa_m R$ of the COD plasma (R is the typical linear dimension of the COD which, at high pressures, does not exceed 2 mm). Calculations show that reabsorption of thermal radiation by the COD plasma in argon is unimportant up to pressures of 30 atm, i.e., throughout the region of existence of the discharge. In the calculations corresponding to the results of Sec. 3, the temperature was taken to be 12 700°K.

Thus, the formula for the integrated emissive power of plasma given by (3), and the formula given by (7) which is a consequence of it and represents the fraction of line emission, are in good agreement with experimental data in the case of argon. We have no reasons to doubt that these formulas can be successfully applied to other gases. In each case, one must, of course, take into account the particular features of the term scheme for the corresponding atoms and ions.

2. INTEGRATED EMISSIVE POWER OF ARGON PLASMA (EXPERIMENT)

Our aim was to investigate the continuous optical discharge and, at the same time, use it to determine the integrated radiative losses of argon plasma. COD is quite simple to produce. The beam (7) from a high-power CO_2 laser was focused inside chamber (9) (see Fig. 3). The chamber was first exhausted and then filled with the gas under investigation to the required pressure, which, in our experiments on argon, was up to 2 atm. The laser beam power (up to 1 kW) is quite insufficient for spontaneous breakdown in the gas. It is therefore necessary to generate plasma for the initial absorption in the region in which the beam is focused This is done either by initiating gas breakdown with the aid of some other pulsed laser, or by evaporating tungsten under the action of the laser radiation (1). The absorption "nucleus" formed in this way eventually develops into a stable, continuously glowing, optical discharge (10) which is located well away from all surfaces (the tungsten wire is removed after the process has started).

Under our experimental conditions, the COD took the form of an ellipsoid located in the region in which the laser beam was focused. All the measurements were performed in the plane of maximum cross section of this ellipsoid, at right-angles to the axis of symmetry.

The principle of the measurements was as follows. The COD radiation passed through window (5) and was allowed to fall on the flat aluminum mirror (4) which could be rotated. The window material was crystalline NaCl and quartz. Combinations of windows made of these materials enabled us to establish which fraction of the radiation from the discharge was absorbed by each of them in the ultraviolet and infrared regions of the spectrum, respectively. Reflection from the windows was also taken into account experimentally. The mirror (4) reflected the incident radiation onto the concave aluminum mirror (6) which formed an image of the COD on the entrance slit of the recording instrument (2). The recorder used in plasma diagnostics was the STÉ-1 spectrograph with a photoelectric detector and the N-110 strip chart recorder. In the case of the integrated emission, the recording instrument was the open-type thermocouple element working in conjunction with a microvoltmeter. The mirror (6) was equipped with a special device which produced its slow rotation about the vertical diameter. In the case of plasma diagnostics, the COD image was thus made to move along the entrance slit of the spectrograph in the horizontal direction. At the same time, the strip chart recorder drew out the plasma intensity along the chord of the maximum cross section of the plasma as a function of the distance between this chord and the center of the cross section.

When the integrated emission was recorded, the mirror (6) remained fixed in position and the thermocouple sensor was moved across by a micrometer screw. The angular size of the beam of trays leaving the plasma and the ratio of the entrance slit of the recorder to the size of the COD image were small enough to ensure good spatial resolution.

The intensity curves obtained in this way were subjected to the Abel transformation which yielded the radial dependence of the corresponding emissive power (integrated, spectral, or line). The Abel transformation was applied with the aid of tables (see, for example, [14]). The radius was subdivided into 30 intervals.

Plasma diagnostics in the above cross section was carried out by two methods. The first involved measurements of the absolute intensity of the 4806 Ar II line.

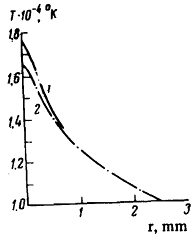

FIG. 4. Experimental temperature profile of COD plasma in the plane of maximum cross section. Pressure 2 atm. 1—based on absolute intensity of 4806 Ar II line; 2—absolute intensity of the continuum.

The above method was used to obtain the radial dependence of the sum of the emissive powers in the 4806 Ar II line and in the continua below and adjacent to this line. The exit slit of the spectrograph was made sufficiently broad to ensure that the total line intensity was recorded. The difference between the resulting curves gave the radial dependence of the total intensity of the 4806 Ar II line. By comparing this intensity with its calculated temperature dependence, we were able to obtain the radial temperature profile. The second method involved measurements of the absolute intensity of the continuum. The resulting radial dependence of the spectral emissive power of the plasma at 4815 Å was compared with the calculated temperature dependence of this quantity. The value of the ξ-factor at this wavelength was taken from[6]. The continuum was calculated from the Biberman-Norman formula (1).

The comparison source (3) was a tungsten ribbon lamp (type Si-8-200U). Absolute calibration was carried out by determining the integrated emission from a tungsten wire leaving the tube with a thermocouple radiometer and with the IMO-2 instrument. The two sets of results agreed to within the experimental error of about 5%. All the measurements were carried out on the same COD.

Figure 4 shows the experimental temperature profile of the COD in the cross section under investigation. The two-diagnostic methods complement one another. The first has high accuracy at the center of the plasma, and the second on the periphery. It may therefore be considered that the plasma temperature has been reliably measured across the entire cross section.

The temperature profile and the profile of the integrated emissive power provided us with the main result of our experiment, namely, the temperature dependence of the latter (see Fig. 1). It is clear from Fig. 1 that the experimental curve is in good agreement with calculations and with the data reported by other workers. According to our estimates, the experimental uncertainty is 10% in the 10 000–13 000°K range and 20% at other temperatures.

3. EMISSIVE MODEL OF THE CONTINUOUS OPTICAL DISCHARGE

Using the above formula for the integrated emissive power, confirmed by experimental data (and also by thermal conductivity data for argon,[15]), one can readily estimate the relative importance of radiation and conduction losses. Consider a sphere of radius r filled with plasma at temperature T. The conduction losses can then be written in the form $W_{cond} = 4\pi\Theta(T)r$, where

$$\Theta(T)=\int_0^T\lambda(T)\,dT$$

is the heat flux potential (λ is the thermal conductivity).

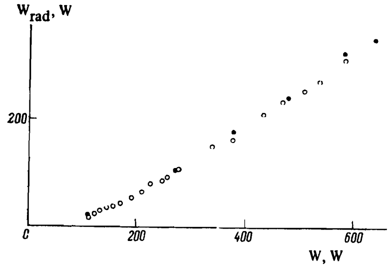

FIG. 5. Power radiated by COD plasma (integrated over the spectrum, the volume of the plasma, and the solid angle) as a function of laser intensity: ●—for p = 6 atm. ○—for p = 10 atm.

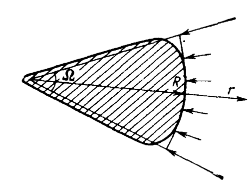

FIG. 6. Mutual disposition of COD plasma and laser beam. Shaded area is occupied by plasma; Ω is the solid angle of the laser beam, R—radius defining the position of the front of the plasma on which $T = T_0$, and $W/\Omega R^2 = S_0$. Large arrows show the direction of the laser beam rays.

The radiation losses are $W_{rad} = {}^4/_3\pi r^3 \cdot 4\pi\epsilon_s(T)$. Their ratio is

$$W_{rad}/W_{cond}=4\pi r^2\varepsilon_s(T)/3\Theta(T) \tag{8}$$

and for p = 10 atm, T = 13 000°K, and r = 2 mm, it is of the order of 10.

In addition to these estimates, we have determined experimentally the fraction of laser power escaping in the form of radiation. To do this, the above thermocouple radiometer was used to measure the total radiation integrated over the spectrum and throughout the volume in absolute units. The results are shown in Fig. 5, from which it is clear that the fraction of power lost by radiation at high beam intensities is 45–55%. Roughly equal losses (50%) can be ascribed to beam power absorbed by the plasma[2] (with allowance for the angular redistribution of the beam). Hence, it is clear that, under the above conditions, practically the entire power absorbed by the COD plasma is lost by radiation.

Therefore, for pressures $p > 5$ atm, and for sufficiently high laser beam power, one can eliminate thermal conduction from the analysis and write the equation for the radiative balance in the form

$$\frac{W}{\Omega r^2}\varkappa\exp\left(-\int_r^R\varkappa\,dr\right)=4\pi\varepsilon_s. \tag{9}$$

This equation is written for a converging laser beam (see Fig. 6). The quantity κ is the absorption coefficient for laser radiation and W is the laser beam power.

For further discussion, it will be very important to consider the properties of the function

$$S(T)=4\pi\varepsilon_s/\varkappa, \tag{10}$$

which is equal to the intensity of the laser radiation at a point at temperature T and which, as will be clear from the ensuing discussion, is independent of pressure. Firstly, we note that, at high pressures, the plasma temperature cannot be high since, otherwise, the absorption coefficient κ would be unrealistically large. According to our estimates, based on experimental data on the COD size and the fraction of absorbed power, the plasma temperature is 12 000–13 000°K. We shall therefore use (3) without allowance for radiation due to ions and calculate ϵ_s. Following Biberman and

Norman,[6] the absorption coefficient can be written in the form

$$\varkappa=4{,}3\frac{N_eN_+e^{-\Delta I/kT}}{(kT)^{1/2}\nu_0^3}\left[\exp\left[\frac{h(\nu_0+\Delta\nu)}{kT}\right]+g-1\right]\frac{h\nu_0}{kT}, \qquad (11)$$

which takes into account stimulated emission. The quantity $h\nu_0$ is the energy of the laser photon (0.117 eV) and g is the Gaunt factor for free-free transitions which, under our conditions, is independent of pressure. Its temperature dependence is also negligible in our range. According to the calculations reported by Karzas and and Latter,[16] we can take g = 1.38.

From (3), (10), and (11), we have

$$S(T)=6.53\cdot10^9\left(\frac{T}{10^4}\right)^2\frac{\exp(h\nu_g/kT)}{g-1+\exp[h(\nu_0+\Delta\nu)/kT]}. \qquad (12)$$

Calculations based on this formula are substantially simplified by the fact that, owing to high electron densities, $h(\nu_0+\Delta\nu)$ reaches its maximum possible value which, for argon, is 0.76 eV. Let us consider this in greater detail. The physical origin of the factor $\exp(h\Delta\nu/kT)$ in (11) is that this factor represents the additional absorption of laser photons due to bound-bound transitions to merged levels very close to the ionization limit. The quantity $h\Delta\nu$ is determined by the electron density and increases with it. However, below 0.76 eV, the argon levels exhibit a gap and are distributed in a very inconvenient way, so that the laser transitions to them are impossible for realistic N_e.

It is clear from (12) that the function S(T) has a characteristic feature, i.e., a minimum $S_0(T_0)$. This means [see (9)] that, when the laser beam intensity is less than S_0, plasma cannot exist. This also means that the minimum possible temperature of the plasma is T_0. In fact, temperatures $T < T_0$ are readily shown to correspond to unstable equilibrium. Conversely, when $T > T_0$, the radiative balance is stable and the plasma temperature at a given point is unambiguously determined by the laser intensity at this point. The temperature T_0 is given by

$$T_0=\frac{h}{2k}\left\{\nu_g-\frac{\nu_0+\Delta\nu}{1+(g-1)\exp[-h(\nu_0+\Delta\nu)/kT_0]}\right\}. \qquad (13)$$

which is readily deduced from (12). For argon, T_0 = 12 700°K.

Therefore, for given laser beam intensity, the COD plasma can exist only within the cross sections of the light cone which are smaller than a certain maximum (see Fig. 6). By virtue of the mechanisms whereby plasma propagates against the beam (thermal conduction, radiation transfer, and so on), the plasma fills the light cone immediately after the maximum possible cross section. The position of this cross section (which coincides with the position of the leading front of the plasma) can readily be obtained from (9):

$$R=(W/\Omega S_0)^{1/2}. \qquad (14)$$

It is clear from the formula that this quantity is practically independent of pressure and is proportional to $W^{1/2}$. The experimental dependences (Fig. 7) are in satisfactory agreement with (14).

Thus, at a given pressure, the plasma continues to move against the beam as the intensity increases. It would appear that there is no limit to this motion as the intensity increases. However, experiment shows that the plasma is extinguished at a certain power W_{max}. This effect was explained in[2] by the floating of the

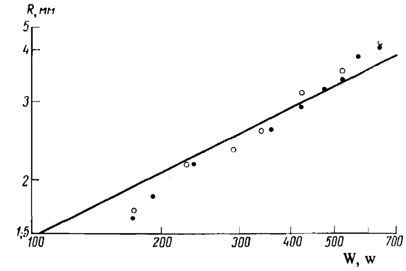

FIG. 7. Position of the leading front of the plasma (measured from the apex of the light cone) as a function of laser-beam power; ●—p = 5 atm, ○—p = 10 atm (both experimental). Solid line shows calculations based on (16). Both scales are logarithmic.

plasma under the action of Archimedean forces, or by the transport of the discharge by gas currents rising out of the focal region. These mechanisms cannot, however, explain the dependence of W_{max} on the pressure. On the other hand, our proposed emissive model of COD is capable of providing this explanation. Qualitatively speaking, the upper limit for the existence of the COD can be explained as follows. In accordance with the foregoing discussion, the temperature inside the discharge cannot be less than T_0. On the leading front of the plasma, it is equal to T_0. This means that the necessary condition for the existence of the discharge is that the temperature should not decrease in the direction into the plasma. Consequently, the intensity of the laser beam should not decrease either. As the beam penetrates the plasma, this intensity decreases because of absorption and increases because of the contraction of the beam in the convergent light cone. As the discharge moves into the regions of increasing cross section of the cone, the importance of the latter effect monotonically decreases, whilst that of the first effect remains constant. Consequently, a point is eventually reached at a certain beam power, where the contraction of the beam cannot compensate its absorption, and the plasma can no longer exist. The greater the pressure, the smaller is the power at which the plasma will become extinguished.

Formally, the position of the leading front of the plasma at the upper limit R_{max} can be found from the equation

$$\frac{d}{dr}\left[\frac{W}{\Omega r^2}\exp\left(-\int_r^R\varkappa\,dr\right)\right]=0. \qquad (15)$$

Differentiating, we find for r = R:

$$R_{max}=2/\varkappa(T_0,p). \qquad (16)$$

From (14) and (16), we have

$$W_{max}=4\Omega S_0/\varkappa^2(T_0,p). \qquad (17)$$

Figure 8 shows the calculated W_{max} together with the experimental curve. It is clear from the figure that the emissive model of COD is in good agreement with experimental values of W_{max}. It is important to note, however, that because of the rapid variation of W_{max} with T, and the uncertainty in T_0, the error in W_{max} is 50%.

It was noted in[2] that, in a vertical beam, the discharge exists even beyond the upper limit. However, it cannot be regarded as stationary: it is highly inhomogeneous in space and time. The mechanism responsible for this behavior is probably as follows. When $W > W_{max}$, the plasma decays for the reasons indicated above. However, the rising currents drag the decaying

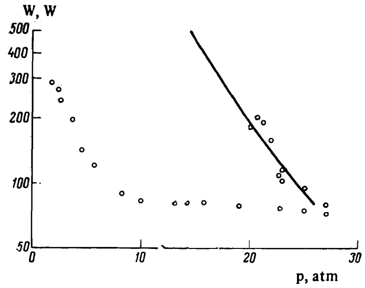

FIG. 8. Calculated upper limit for the existence of COD (solid curve) and the experimental results from. [2]

plasma into the region of maximum laser intensity, which provides a nucleus for the formation of a new discharge. The new plasma suffers the same fate: it begins to decay once it reaches R_{max}. In the case of a horizontal beam, on the other hand, the decaying plasma is, in general, transported out of the light cone and repeated appearance of the discharge is impossible.

We are indebted to Yu. P. Raĭzer for valuable advice and to A. S. Zaĭtsev for his assistance in the experiments.

[1]N. A. Generalov, V. P. Zimakov, G. I, Kozlov, V. A. Masyukov, and Yu. P. Raĭzer, ZhETF Pis'ma Red. 11, 447 (1970) [JETP Lett. 11, 302 (1970)].
[2]N. A. Generalov, V. P. Zimakov, G. I. Kozlov, V. A. Masyukov, and Yu. P. Raĭzer, Zh. Eksp. Teor. Fiz. 61, 1434 (1971) [Sov. Phys.-JETP 34, 763 (1972)].
[3]D. L. Franzen, Appl. Phys. Lett. 21, 62 (1972).
[4]C. D. Moody, Appl. Phys. Lett. 22, 31 (1973).
[5]D. C. Smith and M. C. Fowler, Appl. Phys. Lett. 22, 500 (1973).
[6]L. M. Biberman and G. É. Norman, Usp. Fiz. Nauk 91, 193 (1967) [Sov. Phys.-Usp. 10, 52 (1967)].
[7]G. Ecker and W. Kröll, Phys. Fluids, 6, 62 (1963).
[8]I. T. Yakubov, Opt. Spektrosk. 19, 497 (1965) [Opt. Spectrsoc. 19, 277 (1965)].
[9]D. L. Evans and R. S. Tankin, Phys. Fluids 10, 1137 (1967).
[10]R. U. Krey and J. C. Morris, Phys. Fluids 13, 1483 (1970).
[11]H. N. Olsen, Physico-Chemical Diagnostics of Plasmas, Proc. Fifth Biennial Gas-Dynamics Symposium, 1964.
[12]W. Weizel and R. Rompe, Theorie el. Lichtbogen, Leipzig, 1949.
[13]U. Bauder, Appl. Phys. 39, 148 (1968).
[14]V. Lohte-Holtegreven, transl. in Metody issledovaniye plazmy (Methods of Investigating Plasma) Mir, 1971.
[15]L. I. Grekov, Yu. V. Moskvin, V. S. Romanychev, and O. N. Favorskiĭ, Osnovye svoĭstva nekotorykh gazov pri vysokikh temperaturakh (Basic Properties of Certain Gases at High Temperatures), Mashinostroenie, 1964.
[16]W. J. Karzas and R. Latter, Astrophys. J., Suppl. Ser. 6, 167 (1961).

Translated by S. Chomet
100