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A SEMI-SELF-MAINTAINED VOLUMETRIC DISCHARGE IN ITS OWN MAGNETIC FIELD

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A volumetric discharge excited in a gas by an electron beam has found wide application in electric-ionization lasers [1]. A number of reports have recently appeared in which the influence of the magnetic field of the discharge current and the electron beam on the uniformity of such a discharge is investigated [2-9].

If the discharge power is expressed through the electric field strength and the Larmor radius of the electron beam [4], then the radiant energy Q taken from a unit length of a laser pulse in one pulse can be written in the form

$$Q = 2\eta \frac{1}{e}\frac{E}{p} p t_{\text{pu}} \sqrt{U_b(U_b + 2mc^2)} \frac{d}{r_L}\frac{1}{\eta_0},$$

where E is the electric field strength; d, distance between electrodes; p, pressure of the laser mixture; U_b, energy of the beam electrons; t_{pu}, time of pumping of the active medium of the laser; η, efficiency of conversion of electrical energy into radiant energy; $\eta_0 = (\mu_0/\varepsilon_0)^{1/2}$; μ_0 and ε_0, magnetic permeability and the permittivity of a vacuum; r_L, minimum Larmor radius of beam electrons with an energy U_b in the magnetic field of the discharge current. Means of increasing the radiant energy are obvious from the expression for Q: an increase in the values of the parameters E/p, pt_{pu}, d/r_L, and U_b for the optimum η. Realistic possibilities for varying these parameters have essential limits, however: E/p is limited to the vicinity of values where the pumping of laser levels is efficient and the quantity pt_{pu} is limited by gas heating and by relaxation of the upper laser level [1, 10]; the use of high-energy beams with an energy of 0.5-1 MeV requires special technical equipment and considerably reduces the efficiency of the entire laser system. Therefore, d/r_L is the only free parameter permitting an increase in the radiant energy. Consequently, a detailed investigation of the uniformity of a semi-self-maintained discharge in its own magnetic field must precede the creation of superpowerful laser systems.

The influence of a magnetic field on the distribution of beam ionization losses was first studied theoretically in [2, 3] by the Monte Carlo method. The self-consistent problem of the uniformity of a discharge in its own magnetic field was analyzed in [6], a nonsteady solution without allowance for scattering of beam electrons was obtained in [8], and a model kinetic equation for beam electrons was investigated in [9]. In [5-7] it was shown that for a given magnetic field there exists a limiting beam width, and an increase in beam width beyond it does not result in a change in the active region of the discharge. The existence of an optimum magnetic field providing the best uniformity of ionization losses of the beam and the promise of the use of relatively narrow electron beams ($h < d$, where h is beam width up to the foil) to create superpowerful laser systems are dis-

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cussed in [9]. It must be noted that actual laser constructions have not been considered in any of the theoretical reports devoted to the unifomity of a discharge in its own magnetic field, i.e., several important factors affecting the picture of the process were ignored. For example, in [6], where a statement of the problem best approaching reality was studied, the scattering of beam electrons in the foil and anode of the discharge is ignored. At the same time, the essential influence of scattering in the anode on the distribution of beam ionization losses was shown in [11]. Therefore, the study of a semi-self-maintained discharge in a typical laser construction is of considerable practical interest. The question of the optimum parameters of a laser system enabling one to obtain the maximum laser power without significant degradation of the spatial uniformity of the discharge also remains open.

The stationary, self-consistent, two-dimensional problem of the spatial distribution of electromagnetic field, electron density of the discharge, and discharge power is considered in the present article. The dependence of the spatial uniformity of the discharge on the magnitude of the magnetic field of the discharge current, the beam width, and the energy of the beam electrons is investigated. The self-consistent system of equations [6, 12] describing the semi-self-maintained discharge was solved by the iteration method. The distribution of ionization losses of an electron beam in a gas was found by the Monte Carlo method, and the influence of the electromagnetic field on the motion of beam electrons and of the process of scattering of fast electrons in the foil, gas, and anode of the discharge was taken into account. The length of the laser system was assumed to be much greater than the transverse size of the laser; up to the foil the electron beam was assumed to be monoenergetic and monodirectional; the magnetic field of the discharge current considerably exceeded the magnetic field of the beam current. The creation of discharge electrons resulted from ionization of the gas by the electron beam (allowance for self-ionization insignificantly alters the results [12]) while electron loss was due to recombination processes. The mobility of discharge electrons and the coefficient of recombination were assumed to be independent of the electric field strength; the cathode and anode layers were assumed to be infinitely thin and the voltage drop on them equal to zero. The stationary problem with allowance for the conditions enumerated above satisfactorily describes a real laser system if the time of beam injection considerably exceeds the characteristic time of development of the discharge. Test calculations through the program used showed satisfactory agreement with available experimental and theoretical data on the distribution of beam ionization losses [12].

The majority of calculations were made for a gas mixture CO_2:N_2 = 1:3 at a pressure of $1.01 \cdot 10^5$ Pa; the distance between electrodes was 20 cm; the distance between the aluminum foil with a thickness of 25 μm and the cathode grid with a transparency of 100% was 2 cm; the voltage drop U between electrodes was chosen as 100 kV; the anode of the discharge was assumed to be iron.

A concept of the character of the influence of the magnetic field on the motion of beam electrons can be obtained on the basis of the results of [5, 8], where electron scattering was ignored. In a relatively weak magnetic field the electron beam contracts, and several beam constrictions can form in the gap between electrodes. A sufficiently strong magnetic field turns some of the beam electrons back to the foil, and there exists a limiting width of the discharge region which an electron beam can excite in a given magnetic field. Scattering of beam electrons in the gas and on elements of the laser construction results in spreading of the beam [12], and therefore it is noted in [2] that the influence of elastic scattering and of the magnetic field can be mutually compensating to a certain extent. This results in the existence of an optimum field providing the best uniformity of the discharge [9].

The isolines of the fields $f_1(x, y) = \int\limits_0^x D(x, y)\,dx \Big/ \int\limits_0^l D(x, y)\,dx$ and $f_2(x, y) = \int\limits_0^x M(x, y)\,dx \Big/ \int\limits_0^l M(x, y)\,dx$ [solid and dashed lines in Fig. 1, respectively, h = 20 cm, U_b = 180 keV, d/r_L = 0 (a), d/r_L = 3.6 (b), d/r_L = 6.6 (c)] clearly show the character of the influence of elastic scattering and of the magnetic field of the discharge current on the spatial distributions of beam ionization losses D(x, y) and discharge power M(x, y). Here the y axis is directed along and the x axis across the direction of electron beam injection; l is the distance from the middle of the discharge to the walls of the discharge chamber. Because of the redistribution of the electric field, the isolines of discharge power are less distorted than the isolines of beam ionization losses. The formation of a beam constriction in the middle of the gap between electrodes (Fig. 1c), which was also observed in the experiment of [4], is connected with contraction of the beam in the magnetic field and with scattering of beam electrons in the anode. The average distance which a beam electron travels in moving from cathode to anode and hence the energy losses of fast electrons in inelastic collisions grow with an increase in the magnetic field. The latter fact, together with the blocking of some of the beam electrons, results in considerable nonuniformity of the distributions, not only spatial but also averaged over the transverse coordinate,

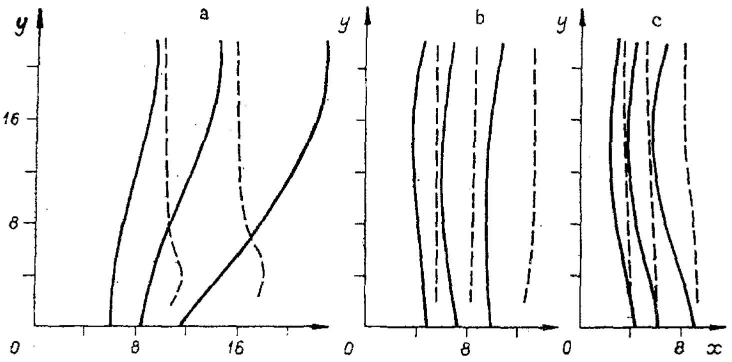

Fig. 1

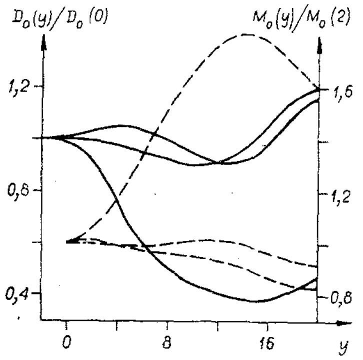

Fig. 2

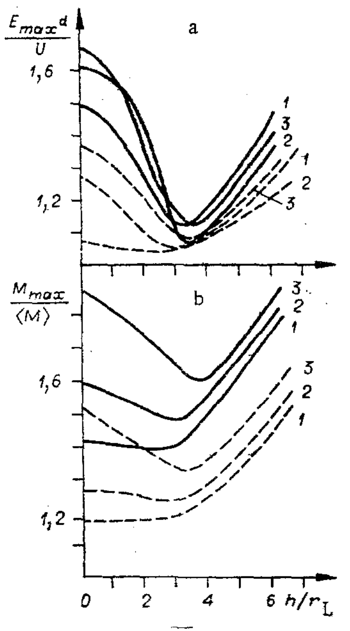

Fig. 3

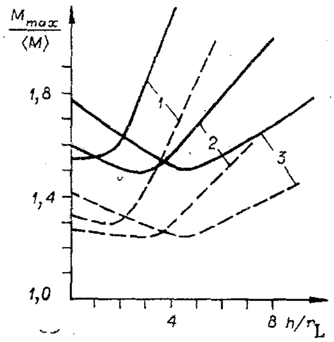

Fig. 4

of the discharge characteristics $D_0(y)=\int_0^l D(x,y)\,dx$ (solid lines) and $M_0(y)=\int_0^l M(x,y)\,dx$ (dashed lines) in a strong magnetic field [Fig. 2, h = 20 cm, U_b = 180 keV, $d/r_L = 0$ (1), $d/r_L = 3.6$ (2), $d/r_L = 6.6$ (3)]. Although the isolines of ionization losses and discharge power give a qualitative idea of the character of the spatial nonuniformity of the discharge, they do not permit a comparison of the uniformity of discharges with different parameters. Therefore, it is desirable to have quantitative integral criteria characterizing the uniformity of a two-dimensional discharge. In the space occupied by the discharge we isolated regions in which 50, 70, and 90% of the total discharge energy is absorbed, respectively, and the criteria of nonuniformity of the discharge in these regions were chosen in the form of the ratios $E_{max}d/U$ and $M_{max}/\langle M\rangle$. Here E_{max}, M_{max}, and $\langle M\rangle = \iint M(x,y)\,dxdy/S$ were found for a region with an area S in which a certain percent of the total discharge energy is absorbed. These criteria are not equivalent to each other, but there is qualitative agreement between them in the description of the nonuniformity of the discharge [Fig. 3, where the dependence of the nonuniformity of the electric field (a) and the discharge power (b) on the ratio h/r_L is shown for different beam widths. The solid lines are the nonuniformity in a region where 90% of the total discharge energy is absorbed while the dashed lines are that for 70%; U_b = 180 keV, h = 40 cm (1), h = 20 cm (2), h = 10 cm (3)]. The optimum magnetic field providing the best discharge uniformity for different beam widths can be determined from the relation $(h/r_L)_{opt} \approx 3\text{-}4$ with the other parameters of the discharge and beam being fixed. It is interesting to note that the character of the dependence of the discharge nonuniformity on the magnitude of the magnetic field with $h/r_L \gtrsim (h/r_L)_{opt}$ is determined only by the value of the parameter h/r_L and does not depend on h/d.

In a weak magnetic field the uniformity of the discharge is degraded with an increase in h/d, and the condition $h \approx (2\text{-}4)d$ must be satisfied in low-power laser systems to achieve satisfactory uniformity of the discharge [12]. Here the optimum energy of the beam electrons can be determined from the results of optimization of the parameters of a one-dimensional discharge. In powerful laser systems an increase in the energy of the beam electrons permits a decrease in the influence of inelastic scattering on the motion of the fast electrons and hence an increase in the value of $(h/r_L)_{opt}$ [Fig. 4, where the dependence of the nonuniformity of the discharge power on the ratio h/r_L is shown for different energies of the beam electrons. The solid lines are the nonuniformity in a region where 90% of the total discharge energy is absorbed while the dashed lines are that for 70%; h = 20 cm, U_b = 150 keV (1), U_b = 180 keV (2), U_b = 210 keV (3)]. An increase in the electric field strength gives a similar effect.

To achieve satisfactory uniformity of the discharge for the maximum radiant energy from a unit length of laser one must satisfy the condition $h/r_L \approx (h/r_L)_{opt}$. Then the expression for the radiant energy can be written in the form $Q \sim (d/h)(h/r_L)_{opt}$. For a given $(h/r_L)_{opt}$, therefore, the radiant energy can be increased by increasing the ratio d/h. The strongest lower limit on the width of the electron beam is connected with the dependence of the efficiency of conversion of the energy introduced into the discharge into radiant energy on the specific density of applied energy, $d/p = \langle M\rangle t_{pu}/p$. In [10] it was shown that the efficiency of a laser system declines at $d/p \gtrsim (q/p)_*$. Starting from the ratio $d/p = (q/p)_*$, the expression for the optimum width of the electron beam can be written in the form

$$h^2 = 2/\eta_0 e\,(E/p)\,t_{pu}\sqrt{U_b\,(U_b + 2mc^2)}\,(h/r_L)_{opt}\,(q/p)_*^{-1}.$$

If we take the typical parameters of a laser system as $E/p \sim 0.075$ V/cm/Pa, $(q/p)_* \approx 0.5 \cdot 10^{-5}$ J/cm³/Pa, $p \sim 1.01 \cdot 10^5$ Pa, $t_{pu} \approx 2 \cdot 10^{-6}$ sec, U_b = 200 keV, and $(h/r_L)_{opt} \sim 4$, we can obtain a value of h ~ 20 cm for the optimum beam width. Preliminary calculations showed that by using an electron beam with an electron energy $U_b \approx$ 250-300 keV one can excite a semiself-maintained discharge with d = 40-50 cm having a satisfactory uniformity. This permits an increase of about 5-8 times in the radiant energy from a unit length of laser with the optimum values of h and h/r_L in comparison with the limiting energy given in [4]. Thus, the results of the present work permit the choice of the optimum discharge geometry and power in the construction of superpowerful, electric-ionization laser systems.

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