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UNIFORMITY OF A VOLUMETRIC DISCHARGE CONTROLLED BY AN ELECTRON BEAM IN A TRANSVERSE MAGNETIC FIELD

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The unique properties of electric-ionization CO_2 lasers, the possibility of the direct convesion of the energy of an electric field into coherent radiation with an efficiency of ~ 30%, and the high specific characteristics of the active medium open up broad prospects in the field of the creation of powerful installations with energies of 1-10 kJ per pulse [1-3]. The use of superpowerful CO_2 laser systems for the solution of a number of scientific and technical problems [4, 5] imposes rather strict limits on the quality of the optical characteristics of the beam of coherent radiation, determined primarily by the uniformity of the volumetric discharge. The investigation of the main physical processes responsible for the uniformity of the absorption of electrical energy in the volume of the discharge gap is urgent in this connection.

It was shown in [6, 7] that in volumetric discharges of high power excited by an electron beam it is necessary to allow for the influence of the intrinsic magnetic field of the current of the primary discharge on the distribution of ionization losses of the beam of fast electrons. Actually, the magnetic field produced by the current of a volumetric discharge, with allowance for its typical geometry $d \approx h << l$ (d is the distance between the electrodes, h is the width of the discharge, and l is its length), is described by the relation

$$H = \frac{4\pi}{c}\int\limits_0^{h/2} j\,dh \simeq \frac{2\pi}{c} j_0 h,$$

where j_0 is the average current density of the volumetric discharge. Consequently, in the approximation $j_0 \simeq \text{const}$ over a cross section of the discharge H grows linearly from the center to the boundary of the discharge. For typical parameters of an electron beam of 0.2-0.5 MeV and a size $d \approx 10$ cm for the discharge gap a magnetic field of 0.5-1 kOe can assure the capture of electrons into Larmor orbits of $r_L < d$ regardless of ionizing collisions with neutral gas molecules. In this case the drift of the injected electrons must lead to constriction of the beam into the region of the minimum value of H.

The results of preliminary experiments on a study of the influence of a constant transverse mangetic field on the electrical characteristics and current distribution of a volumetric discharge are reported in the present article. The magnetic field configuration was chosen as close to the actual one produced by the current of the discharge.

A schematic diagram of the experimental installation is presented in Fig. 1. An electron beam with a current of up to 100 A, a maximum energy of 150 keV, a duration of 10^{-8} sec, and a cross section of 8 × 80 mm, produced by a special electron accelerator [8], was injected through titanium foil 12 μm thick into the discharge gap, formed by a high-voltage electrode 1 and a metal grid 2 with a transmittance of 0.6. The distance between the electrodes was regulated within limits of 3-7 cm. To measure the current distribution

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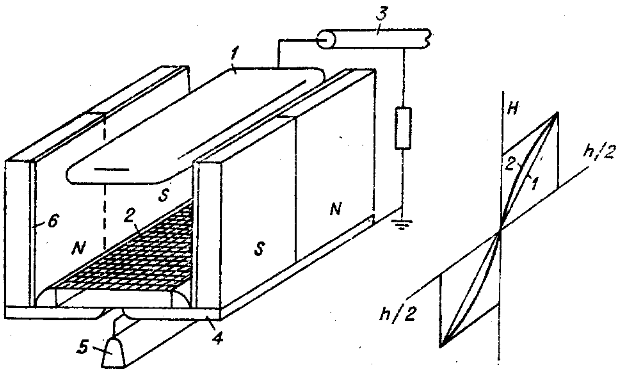

Fig. 1

of the discharge the high-voltage electrode was sectioned lengthwise (eight sections). Electrical decoupling between the sections 8 mm wide was provided by dielectric spacers 2 mm thick. An electrical line 3 with a wave impedance $\rho << R_d$ (R_d is the resistance of the discharge gap) was connected to each section, which made it possible to maintain a constant value of E/p during the entire stage of current flow through the volumetric discharge. The chosen magnetic field configuration 2 (see Fig. 1) simulated the actual field of a current sheet with a length $\Delta l \simeq 8$ mm and a width $h \simeq 80$ mm. The external magnetic field was produced with permanent magnets whose location is shown in Fig. 1. Influence of the magnetic field on the operation of the electron gun of the accelerator 5 was eliminated by magnetic shielding 4 and was monitored by independent measurements of the current of the injected beam with and without the presence of the magnetic field. The discharge gap was confined by dielectric plates 6.

The quantity H was determined by the number of magnetic plates, while the value of the field and its distribution in the discharge gap were measured with a Hall-effect gaussmeter with a spatial resolution of ~ 3 mm. The beam current I_b was measured with a Faraday cylinder with a time resolution of $\sim 2 \cdot 10^{-9}$ sec. In an experiment the total discharge current I_d and its distribution were monitored by independent ohmic shunts connected directly to the discharge circuit of the electrical lines. The resistance of each shunt was $R_{sh} \simeq 0.1\,\rho$. The error of the current measurement did not exceed 15%. In addition, the integral emission of the gas in the volumetric discharge was recorded in the direction perpendicular to the plane of propagation of the electron beam. During the photography the magnetic plates were only mounted on one side of the discharge gap.

Typical oscillograms of the discharge current and the current of the electron beam are shown in Fig. 2. The initial conductivity in the volumetric discharge is created during the injection of fast electrons for $\sim 10^{-8}$ sec. The dynamics of the flow of the discharge current is subsequently determined by the rate of extinction of electrons in the gap. The influence of the magnetic field shows up in the time variation of I_d. This effect is manifested most strongly at the boundary of the discharge where the magnetic field strength H reaches the maximum value.

In Fig. 3 we present the dependence of the total discharge current in relative units, I_{dH}/I_{d0}, on the parameter d/r_L, where r_L is the Larmor radius of electrons of the injected beam corresponding to the maximum value of the magnetic field; I_{d0} is the discharge current without a magnetic field. The dependence of the total discharge current in a uniform transverse magnetic field (points 1) is shown here for comparison. A characteristic feature of these dependences is the presence of a corresponding value of the critical field of the parameter d/r_L, exceeding which leads to a considerable decrease in the discharge current. In contrast to a uniform magnetic field, the influence of a nonuniform field (points 2) is manifested in some growth of the total discharge current, the value of which reaches a maximum at a value of the parameter d/r_L of $\simeq 2.3$.

The results of measurements of the current density distribution of the volumetric discharge along the sectioned electrode in a nonuniform magnetic field are shown in Fig. 4 (1-3: $d/r_L = 4.2$, 2.3, and 1.7, respectively); it is seen that a magnetic field $H \simeq 400$ Oe ($d/r_L \simeq 1.7$) weakly disturbs the current distribution of the discharge. With an increase in H to 540 Oe one observes its redistribution, accompanied by a considerable increase (by about twofold) in the current density in the region of the minimum value of the magnetic field. A further increase in H leads both to distortion of the initial distribution and to a decrease in the total current of the volumetric discharge.

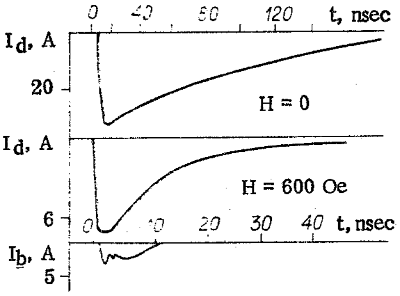

Fig. 2

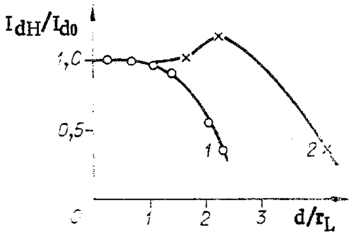

Fig. 3

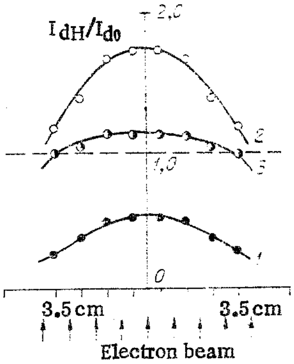

Fig. 4

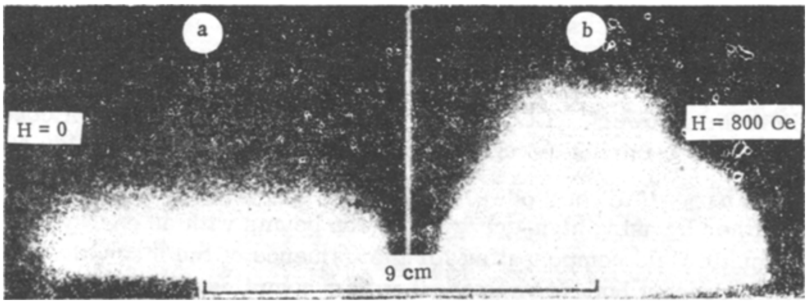

Fig. 5

The pattern of integral emission of the gas in the volumetric discharge with H = 0 and 800 Oe is shown in Fig. 5a, b, respectively; it is seen that a nonuniform magnetic field promotes the constriction of the electron beam into the region of the minimum H and determines and increase in the degree of ionization of the gas at the center of the gap. Under the conditions of the experiment the process of energy loss of fast electrons leads to more intense ionization of the gas at distances of ~ 2 r_L from the side of beam injection, which is in good qualitative correspondence with the results of a numerical calculation made in [7]. The constriction of the beam results in growth of the total discharge current with an increase in the gap $d \leq 2r_L$ between the electrodes, but in this case also, as seen from Fig. 4, the current density distribution along the length of the gap proves to be considerably nonuniform. A further increase in the magnetic field, which corresponds to the condition $d > 2r_L$, leads to the appearance in the discharge gap of a layer of weakly ionized gas, causing a sharp decrease in I_d. The faster decrease in the discharge current with time observed in tests with a magnetic field present is evidently connected with the considerable nonuniformity of the gas ionization and a corresponding redistribution of the electric field.

Thus, the experiments conducted showed that significant nonuniformity of the current density distribution, and hence of the absorbed electrical energy, develops in a nonuniform magnetic field simulating the intrinsic magnetic field of a high-current volumetric discharge.

The amount of energy absorbed in a volumetric discharge is determined by the expression

$$Q \simeq \int_0^{t_a} I_d U_0 dt \simeq d\left(\frac{E}{p}\right) p \int_0^{t_a} I_d dt,$$

where I_d is the discharge current; U_0 is the voltage on the discharge gap; t_a is the duration of energy absorption.

If as the criterion for weak disturbance of the current distribution of the volumetric discharge we take the value $d/r_L \simeq 1.7$ established experimentally, then, using the equation

$$r_L \simeq 1.7\cdot 10^3 \frac{eU_b}{m_0c^2}\sqrt{1+\frac{2m_0c^2}{eU_b}}\,\frac{1}{H}, \quad H \simeq \frac{2\pi}{c} I_d \frac{1}{l},$$

for the Larmor radius of electrons of the injected beam with an energy of 200 keV, we can obtain the limiting value of the electrical energy absorbed in a volumetric discharge uniform in cross section:

$$Q \simeq 5\cdot 10^3 p \left(\frac{E}{p}\right) t_a l. \tag{1}$$

For a non-self-maintained, volumetric discharge the parameter E/p is bounded. In CO_2 laser systems the value of the parameter $E/p \approx 5$-15 V/cm·mm Hg depends on the composition of the working mixture and is chosen with allowance for the maximum efficiency $\eta \approx 0.3$ of conversion of electrical energy into radiant energy [9, 10]. Therefore, the condition (1) determines the limiting absolute energy modulus of a powerful volumetric discharge which it is desirable to use for the uniform excitation of the active medium in the entire working volume.

For typical parameters of a CO_2 laser system of the electric-ionization type (working gas mixture $1CO_2:1N_2$ at $p \approx 1$ atm, beam duration $\sim 2\cdot 10^{-6}$ sec, efficiency $\eta \approx 0.3$, $E/p \simeq 10$ V/cm·mm Hg) we obtain, using Eq. (1) for the emitted energy,

$$Q/l \simeq 2 \text{ kJ/m},$$

which is the energy limit for a powerful CO_2 laser system with a uniform flux of coherent radiation, due to the necessity of allowing for the intrinsic magnetic field of the current of the volumetric discharge.

An increase in the energy limit of a powerful CO_2 laser system to $Q/l > 2$ kJ/m can evidently be achieved in two ways: either by using high-energy electron beams with an energy of $\gtrsim 1$ MeV or by the creation of an external magnetic field compensating for the influence of the magnetic field of the current of the volumetric discharge. At present both ways present rather complicated technical problems and lead to additional unjustified energy expenditures, lowering the efficiency of the laser system as a whole.

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