Distribution of the charged particles of a gas-discharge laser plasma in a transverse magnetic field. II. Experimental study

S A Martsinukov and D K Kostrin
Department of electronic instruments and devices, Saint Petersburg Electrotechnical University “LETI”, 197376, Saint Petersburg, Russia

E-mail: sergm2006@mail.ru

Abstract. The paper presents an experimental verification of the adequacy of a physical and mathematical model describing the influence of an external transverse magnetic field on the distribution of the charged particles in a positive column of a gas discharge. A gas-discharge laser located in a transverse magnetic field was used to conduct the study. The vacuum installation allows pumping out the system and feeding the gas mixture into it under a certain pressure. The data obtained during the experiments differ from the calculated ones by no more than 4–5%.

Under the influence of a magnetic field, the operating mode of a gas laser is modified. The magnetic field leads to the Zeeman dividing of the main levels of the gas molecule. This effect provides several magneto-optical impacts, consisting in a change in the insensitivity, laser frequencies and polarization degree of the radiation. Intense magnetic field leads to the alteration of the characteristics of the gas discharge plasma: concentration of electrons and their temperature, which define the speed of “pumping” to the higher laser level. Moreover, the magnetic field alters the state of the gas discharge plasma and reallocates the charged particles in the working volume.

Structurally, the active element of a soldered CO$_2$ laser (figure 1) is a glass or quartz discharge tube with a diameter of fractions to several centimeters and a length of fractions to several meters [1, 2]. The tube is surrounded by a water cooling jacket, a ballast volume is coaxially located around it, connected to the discharge channel.

Figure 1. Scheme of the discharge tube of a CO$_2$ laser: 1 – cathode; 2 – anode; 3 – “blind” mirror; 4 – discharge capillary; 5 – water cooling jacket; 6 – ballast volume; 7 – connecting pipe; 8 – exit window.
The ballast volume increases the total gas reserve, thereby reducing the degree of influence of the dissociation of carbon dioxide molecules in the discharge on the stability of the composition of the active medium. Exit windows and mirror substrates are made of materials that are transparent to infrared radiation: germanium, zinc selenide, gallium arsenide. The required reflection coefficient of the working mirror is achieved by applying quarter-wave layers with alternating high and low refractive indices to the substrate. A non-working, “blind” mirror is made in the form of a gold, copper or aluminum coating applied to a metal or quartz substrate. The output window, to reduce power loss during its reflection, is located at the Brewster angle.

The curves of the constant concentration of electrons and ions in the transverse section of the laser tube are presented in figure 2. It shows that the influence of the transverse magnetic field leads to the compaction of the studied plasma in the local region near the surface of the tube [3, 4]. In this case, the nodal zone undergoes a shift from the initial position at the intersection of the axes to a certain distance towards the dielectric wall.

![Figure 2](image-url)

**Figure 2.** Concentration of electrons and ions in the transverse section of the laser tube.

The distribution of the charged particles along the x axis, in the destination of which the plasma shift occurred, under the influence of different magnetic field forces is shown in figure 3 ($B_0 < B_1 < B_2$). In the absence of the magnetic field, a distribution of a symmetric shape is observed. In the presence of magnetic field, the largest value of $n$ is shifted from the center to the wall, while the direction of drift is determined by the orientation of the both effecting fields – electric and magnetic. According to the condition of the particle balance in the positive column of the electric discharge, the area under the curves should remain constant.

![Figure 3](image-url)

**Figure 3.** Distribution of electrons and ions along the $x$ axis under the influence of a magnetic field.

The regime of recombination in volume is common for the situation when the pressure level of the working gas is at least 10 torr. During the volume recombination process, the electrons that appeared in the nodal zone of the system are not able to reach the surface of the tube. This phenomenon causes compression deformation of the positive column. The expression describing the equilibrium state for the concentrations of charged particles in the considered situation takes the following form:
\[
\text{div}(nV) = z_n - \alpha_{rec}n^2,
\]
where \(\alpha_{rec}\) – coefficient of volume recombination.

If the system under consideration is not affected by external forces, then you can use the value \(\mathcal{V} = (\alpha_{rec}/z_i)n(0)\) to find a solution to expression (1). When \(\mathcal{V} < 1\) the solution of the equation is a power series, and the distribution of the charged particles over the radius actually has a form \(J_0(2.405(r/R))\), i.e., as in the situation when the influence of volume recombination was not considered. When \(\mathcal{V} > 1\) the solution of the equation cannot be obtained, but it can be argued that from the point of view of physics, the distribution of the charged particles will be “U-shaped” in most of the section of the positive column of an electric discharge (especially at \(\mathcal{V} >> 1\)), \(n(r) \approx z_i/\alpha_{rec} = \text{const}\).

Only near the walls in the region of the order of thickness \(\sqrt{z_i/D_a}\), the concentration of charge carriers changes from \(z_i/\alpha_{rec}\) to zero.

Let’s estimate \(\mathcal{V}\) for a molecular CO\(_2\) gas laser with the following parameters: \(p = 8...13\) torr; \(n_e = 10^{16}...10^{18}\) m\(^3\); \(z_i = 1\) m\(^{-1}\); \(\alpha_{rec} = 10^{-14}...10^{-15}\) m\(^3\)/s. Then \(\mathcal{V} \approx 10\). Thus, in a rough approximation, the distribution of the charged particles along the radius is quite close to \(J_0(2.405(r/R))\), i.e., the effect of volume recombination can be ignored.

It is obvious that under the influence of a transverse magnetic field on the positive column of an electric discharge flowing in the gas-discharge laser, the distribution of the charged particles along the radius is determined by the expression

\[
n(r) = n(0)\exp\left(-\frac{b}{2D_a} r\cos\varphi\right)J_0\left(2.405\frac{r}{R}\right).
\]

This equation can be used for approximate calculation of the characteristics of gas lasers, if the pressure of the working mixture is not much more than 10 torr.

Based on the analysis of the charged particles distribution, we can determine the deviation \(x_m\) at which the particle density has the greatest value. The concentration of charged particles from the expression (2) can be written as

\[
n_i = n_0(B)\exp\left(-\frac{b}{2D_a} x\right)J_0\left(2.405\frac{x}{R}\right),
\]

where \(n_0(B)\) – concentration of the charged particles at \(r = 0\). For a certain value of the magnetic field induction, we can assume that \(n_0(B) = \text{const}\). The highest value \(n_i\) is achieved in the case of a positive extremum of the function

\[
f(x) = \exp\left(-\frac{b x}{2D_a}\right)J_0\left(2.405\frac{x}{R}\right).
\]

Instead of an expression \(J_0(2.405(r/R))\) without significant loss of accuracy, an expression of the form \(\left(1 - \left(x^2/R^2\right)\right)\) can be used. Considering \(f(x)\), we can say that the highest value is achieved when

\[
x = x_m = \frac{2D_a}{b} - \sqrt{\frac{4D_a^2}{b^2} + R^2}.
\]

The value \(x_m\) has a negative sign (see figures 2, 3), since the plasma of the electric discharge is shifted towards the negative part of the \(x\) axis. Let’s perform the calculation of \(x_m\) for the discharge in the CO\(_2\) gas (\(\mu_0 = 30\) m\(^2\)/(V-s-torr), \(\mu_e = 0.07\) m\(^2\)/(V-s-torr), \(E = 1.7 \times 10^7\) V/m, \(T_r = 3 \times 10^4\) K, \(R = 10^{-2}\) m). The dependence \(x_m = f(B)\) at different gas pressures is shown in figure 4.
Figure 4. Displacement of the highest concentration point of electrons and ions in plasma under the influence of an external magnetic field at different gas pressures: calculation (1 – \( p = 10 \) torr; 2 – \( p = 18 \) torr) and experimental (x – \( p = 10 \) torr; o – \( p = 18 \) torr) results.

Figure 4 shows that with an increase in the pressure of the gas mixture and with a constant shift of the plasma, the required magnetic field for displacement increases. Let’s rewrite \( x_m \) in another form:

\[
x_m = -\frac{R^2}{2D_b - \frac{4D_a}{b^2} + R^2} \]

Based on \( D_a = \left( \frac{kT_e}{e} \right) \mu_1 \), \( b = \mu_2 \mu_1 E B \) we get:

\[
x_m = -\frac{R^2}{2kT_e}{e\mu_1 EB} \left[ \frac{2kT_e}{e\mu_1 EB} \right] + R^2 \]

Let’s conduct an experimental verification of the adequacy of the considered physical model. The basic block diagram of the installation for the experimental study of the shift of the highest concentration point of electrons and ions is presented in figure 5. It is estimated that the zone with the maximum concentration of electrons and ions is characterized by the maximum luminosity due to the fact that the processes of active excitation of atoms, molecules and ions of the gas mixture are observed in it.

Figure 5. Block diagram of the experimental unit: 1 – laser tube; 2 – vacuum pumping installation; 3 – optical fiber; 4 – amplification scheme; 5 – oscillograph.

The gas-discharge laser is located under the effect of a magnetic field [5] and is plugged to a vacuum installation, which makes it possible both to pump out the tube and to let a gas mixture with a given pressure into it. An optical fiber was applied for acquisition of the light intensity allocation produced by the discharge. One tip of the optical fiber was pushed vertically along the discharge tube, another tip was linked to the amplification scheme. The processed signal is sent to the measuring unit. At \( B = 0 \), the light guide is directed to the node zone of the system corresponding to the maximum signal...
at from the measuring unit. If the magnetic induction fluctuates, the zone characterized by the brightest glow begins to move along the vertical axis. By shifting the optical fiber up or down to the moment when the highest signal value is fixed from the measuring unit, it is possible to find the position that determines the shift of the highest value of the charged particles concentration from the starting point. The shift functions obtained as a result of experiments of the largest value of the concentration of electrons and ions with the alteration of the magnetic induction for several pressures are presented in figure 4. The discrepancy between the calculation and measurement results is less than 4–5 %.

References
[1] Chernigovskiy V V, Martsinukov S A, Kostrin D K and Kiselev A S 2018 IOP Conference Series: Materials Science and Engineering 387 012011
[2] Martsynyukov S A, Kostrin D K, Chernigovskiy V V and Lisenkov A A 2018 Biomedical Engineering 2 77–9
[3] Chernigovskiy V V, Kostrin D K, Martsinukov S A and Lisenkov A A 2016 Vakuum in Forschung und Praxis 6 34–7
[4] Chernigovskiy V V, Martsinukov S A and Kostrin D K 2019 Journal of Physics: Conference Series 1313 012010
[5] Martsinukov S A, Kostrin D K, Chernigovskiy V V and Lisenkov A A 2016 Journal of Physics: Conference Series 729 012023