Laser-induced gas breakdown in a constant magnetic field

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The dependence of the threshold for optical breakdown in gases on the intensity of a constant magnetic field directed parallel to the laser beam is determined. Field of intensity $H \gtrsim 10^2$ kOe are found to lower the breakdown threshold radiation intensity several times at gas pressures $p \sim 1$ atm and more than ten times at pressures $p \sim 0.1$ atm.

Optical breakdown in a constant magnetic field has been investigated in a number of experiments[1-6]. A lowering of the threshold for optical breakdown in gases in a strong magnetic field and an increase in the brightness, and a change in the shape, of the spark have been observed. The expansion of the plasma was not spherical, but occurred mainly along the field. In[4,5], CO_2-laser-induced optical breakdown in helium and argon was investigated. The minimum gas pressure p at which optical breakdown occurred was determined as a function of the intensity H ($0 \le H \le 10^2$ kOe) of a constant magnetic field directed parallel to the laser beam. The shape and dimensions of the focal spot were not measured; therefore the radiation intensity is not known, but all the laser pulses were considered identical. The results of the experiment have been discussed twice[4,5] with considerable discrepancies between the data, which is an indication of the low accuracy of the measurements. Especially striking is the discrepancy between the pressures at which the breakdown occurred in zero magnetic field (90 Torr [5] and 67 Torr[4] for argon).

To explain the results obtained in[4] by Cohn et al., a relation between the breakdown gas pressures in nonzero and zero magnetic fields is derived from the condition for breakdown[1)]. Besides p_0 (the breakdown pressure at H = 0), another empirical parameter R characterizing the focal region ($R = l_0/r_0$, where $2l_0$ and r_0 are the length and radius of the cylindrical focal region) was used in the derivation. Agreement with the experimental results can be achieved by taking R = 2.2 for argon and R = 1.4 for helium, which is wrong, since the shape of the focal region does not depend on the properties of the gas. Also false is the observation that R could be pressure dependent. To explain the results obtained in[5], we must take R > 6, which cannot be for a spherical mirror of focal length f = 2.1 cm and a beam diameter A = 2.5 cm.

The aim of the present note is to carry out a more rigorous investigation of laser-induced gas breakdown in the presence of a constant magnetic field. This can be done by determining the rate of avalanche development from the diffusion equation.

The mechanism underlying the optical breakdown induced by laser pulses of duration $\tau \gtrsim 10^{-8}$ sec in gases at not too low pressures is the electron avalanche. The electron concentration in the focal region increases within the duration of a pulse from a startup to the breakdown value, i.e., the value at which the focal region becomes opaque to the radiation, as a result of which a significant portion of the pulse energy is released in the small focal region. During the development of the avalanche, the electrons are heated up through collisions with the atoms in the radiation field, and after gaining sufficient energy, they excite or ionize the atoms of the gas. Part of the energy is transferred to the atoms in inelastic collisions. The variation of the electron temperature in the avalanche is described by the equation

$$\frac{3}{2}n\frac{dT}{dt}=\frac{4\pi e^2 n\nu}{mc(\omega^2+\nu^2)}q-\frac{3m}{M}n\nu(T-T_a)-(I+2T)n\nu_i-(I^*+T)n\nu^*. \quad (1)$$

Here n and T are the density and temperature of the electrons, q and ω are the intensity and frequency of the radiation, T_a and M are the temperature and mass of the gas atoms, I and I^* are the ionization and excitation potentials of the atoms in the ground state, and ν is the electron-atom elastic collision rate.

Since the rates of ionization and excitation of the atoms by electron impact, ν_i and ν^*, exponentially increase with increasing electron temperature (see, for example,[7]), the electron temperature in the wave field increases only to some value determined by the radiation intensity and the properties of the gas, after which the cascade develops at constant electron temperature.

Depending on the frequency and intensity of the radiation, the excitation of the atoms can facilitate or impede the development of the avalanche. If the excitation of an atom is quickly followed by its photoionization, then the electron energy goes into the development of the avalanche, otherwise the electron energy is expended nonproductively on the multiplication process. The probability w of a rapid ionization of an excited atom by electron impact is small, since this process corresponds to two almost simultaneous collisions of the atom with two electrons when the degree α of ionization is small ($\alpha = n/N$, where N is the atom density). Obviously, $w \sim \alpha^2$.

If the excited atoms are quickly photoionized, then the electron production rate $\tilde{\nu} = \nu_i + \nu^*$, otherwise an electron is produced only in the ionization of an atom from the ground state by electron impact. For a radiation frequency $\omega \ll (I - I^*)/\hbar$ the excitation of the atoms impedes the development of the avalanche. If, on the other hand, $\omega \lesssim (I - I^*)/\hbar$, then the role of the excited states depends on the radiation intensity. For helium, for example, it is easy to show, using the results obtained in[8] by Bakos et al., that the three-photon ionization of the states 2^1S and 2^3S by rubidium-laser radiation of intensity 10^{10} W/cm^2 has a probability $\sim 10^{15}$ sec^{-1}, i.e., it leads to the appearance of $\sim 10^6$ electrons per nsec. It is shown by Mul'chenko in[9] that the process of two-quantum photoionization of excited neon atoms by rubidium-laser radiation is effective even at the comparatively low radiation intensities that induce breakdown in neon gas at a pressure of 80 atm.

Electron diffusion out of the focal region, described by the equation

$$\frac{\partial n}{\partial t}-\frac{\partial}{\partial x_i}D_{ik}\frac{\partial n}{\partial x_k}=\tilde{\nu}n, \quad (2)$$

slows down the development of the avalanche, but a magnetic field parallel to the radiation flux impedes the diffusion in the transverse direction and facilitates the optical breakdown of the gas:

$$D_\parallel=\frac{\overline{v^2}}{3\nu},\quad D_\perp=\frac{D_\parallel}{1+\omega_c^2/\nu^2},\quad \omega_c=\frac{eH}{mc}.$$

Here $D_\parallel$ and $D_\perp$ are the coefficients of electron diffusion along and across the magnetic field, and v and ω_c are the thermal velocity and the cyclotron frequency of the electrons.

Let us consider a simple model for optical breakdown. Let the radiation intensity $q(\mathbf{r}, t)$ change little during the avalanche-development time τ, and let it be equal to q_0 inside a cylinder of radius r_0 and height $2l_0$ and zero outside this cylinder. The electrons going out of the focal region lose energy in collisions with atoms, but do not absorb radiation; therefore, the rate of electron production outside the focal region also vanishes:

$$\bar\nu=\begin{cases}\bar\nu_0, & r<r_0 \text{ and } |z|<l_0\\ 0, & r>r_0 \text{ or } |z|>l_0\end{cases}.$$

Here we have introduced a cylindrical system of coordinates with the z axis directed parallel to the radiation flux and the magnetic field and with the origin at the focal point of the optical system.

It is convenient to represent Eq. (2) in the form

$$\partial n/\partial t-D_\perp\Delta_r n-D_\parallel\Delta_z n=\bar\nu(\mathbf{r})n$$

and seek the solution in the adiabatic approximation:

$$n(\mathbf{r},t)=\sum_\sigma e^{\sigma t}R_\sigma(r,z)Z_\sigma(z).$$

The function $R(r, z)$ should satisfy a Schrödinger-type equation, only the solution with the highest growth rate (the highest value of σ) being of interest in the present problem:

$$\{D_\perp\Delta_r+D_\parallel\Delta_z+\bar\nu(r,z)-C(z)\}R(r,z)=0.$$

The eigenvalue $C(z)$ is the potential in the equation for the function $Z(z)$:

$$\Delta_z Z+D_\parallel^{-1}\{C(z)-\sigma\}Z=0. \tag{3}$$

If the focal region has the form of a long cylinder (i.e., if $r_0 \ll l_0$), then the adiabaticity condition

$$D_\perp\Delta_r R\gg D_\parallel\Delta_z R$$

is satisfied. In the region $z > l_0$ the only solution to the equation

$$\Delta_r R+D_\perp^{-1}\{\bar\nu(r,z)-C(z)\}R=0 \tag{4}$$

that satisfies the condition $R \to 0$ as $r, z \to \infty$ and tends to a finite value as $r \to 0$ is the trivial solution $R(r, z > l_0) = 0$. The eigenvalue $C(z)$ then remains indeterminate, and it is convenient to consider it equal to zero:

$$C(z>l_0)=0.$$

In the region $z < l_0$ the solution to Eq. (4) that is continuous at $r = r_0$ and that has on this surface a continuous first derivative is given by[10]

$$R(r,z<l_0)=\begin{cases}B_1J_0(rr_0^{-1}p_\perp(1-\lambda_\perp)^{1/2}), & r<r_0\\ B_2K_0(rr_0^{-1}p_\perp\sqrt{\lambda_\perp}), & r>r_0\end{cases}.$$

Here $p_\perp \equiv r_0(\tilde\nu_0/D_\perp)^{1/2}$ and $\lambda_\perp \equiv c/\tilde\nu_0$. The constants B_1 and B_2 are determined from the requirement that R and R'_r be continuous at $r = r_0$. Using the matching conditions at $r = r_0$ to eliminate B_1 and B_2, we obtain for $\lambda_\perp$ the equation:

$$(1-\lambda_\perp)^{1/2}J_1(p_\perp(1-\lambda_\perp)^{1/2})K_0(p_\perp\lambda_\perp^{1/2})=\lambda_\perp^{1/2}J_0(p_\perp(1-\lambda_\perp)^{1/2})K_1(p_\perp\lambda_\perp^{1/2}).$$

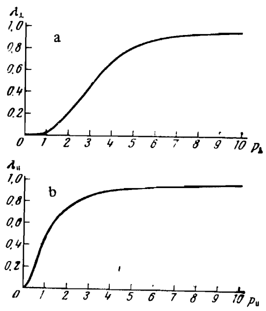

FIG. 1

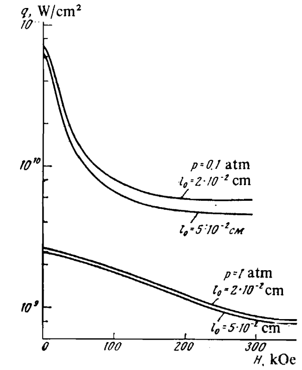

FIG. 2

FIG. 1. Plots of the functions $\lambda_\perp = \lambda_\perp(p_\perp)$, (a), and $\lambda_\parallel = \lambda_\parallel(p_\parallel)$, (b), in the formula (6).

FIG. 2. Threshold for CO_2-laser-radiation-induced breakdown in helium gas in the presence of a magnetic field. $\tau = 10^{-7}$ sec and $r_0 = 5 \times 10^{-3}$ cm.

The solution $\lambda_\perp = \lambda_\perp(p_\perp)$ of this equation is shown in Fig. 1a. Its asymptotic forms for large and small $p_\perp$ are given by the formulas

$$\lambda_\perp=\begin{cases}1{,}26p_\perp^{-2}\exp(-4/p_\perp^2), & p_\perp\ll 1\\ 1-5{,}76p_\perp^{-2}+11{,}5p_\perp^{-3}, & p_\perp\gg 1\end{cases}.$$

The eigenvalue of Eq. (4) is then given by

$$C(z)=\begin{cases}\bar\nu_0\lambda_\perp(p_\perp), & z<l_0\\ 0, & z>l_0\end{cases} \tag{5}$$

The solution of Eq. (3) with the potential (5) is

$$Z(z)=\begin{cases}B_3\cos([(\nu_0\lambda_\perp-\sigma)/D_\parallel]^{1/2}z), & z<l_0\\ B_4\exp(-(\sigma/D_\parallel)^{1/2}z), & z>l_0\end{cases}.$$

This solution is even with respect to z, is continuous at $z = l_0$, and has in the plane $z = l_0$ a continuous first derivative. The constants B_3 and B_4 are determined from the requirement that Z and Z'_z be continuous at $z = l_0$. Using the matching condition at $z = l_0$ to eliminate B_3 and B_4, we can obtain an equation for finding σ.

It is convenient to introduce the notation:

$$\lambda_\parallel(p_\parallel)=\frac{\sigma}{\bar\nu_0\lambda_\perp(p_\perp)},\quad p_\parallel=l_0\left(\frac{\bar\nu_0\lambda_\perp(p_\perp)}{D_\parallel}\right)^{1/2}.$$

The matching condition assumes the form

$$p_\parallel=\frac{1}{(1-\lambda_\parallel)^{1/2}}\operatorname{arctg}\left(\frac{\lambda_\parallel}{1-\lambda_\parallel}\right)^{1/2}.$$

The solution $\lambda_\parallel = \lambda_\parallel(p_\parallel)$ of this equation is shown in Fig. 1b. In the limiting cases

$$\lambda_\parallel=\begin{cases}p_\parallel^2, & p_\parallel\ll 1\\ 1-(\pi/2p_\parallel)^2, & p_\parallel\gg 1.\end{cases}$$

For the characteristic rate σ of development of the avalanche, we obtain the following expression:

$$\sigma=\bar\nu_0\lambda_\perp(r_0(\bar\nu_0/D_\perp)^{1/2})\lambda_\parallel(l_0(\bar\nu_0\lambda_\perp/D_\parallel)^{1/2}). \tag{6}$$

The condition for optical breakdown is the attainment of a definite degree of ionization $\alpha^* \sim 10^{-3}$ [11,12]; therefore, the degree of ionization should increase during the period τ of development of the avalanche from a startup α_0 to the breakdown α^* value:

$$\alpha^*=\alpha_0e^{\sigma\tau},$$

and for this purpose the rate of development of the avalanche should be sufficiently high:

$$\sigma(q_0, p, H, r_0, l_0, \omega, I, I^*) = \tau^{-1} \ln(\alpha^*/\alpha_0). \quad (7)$$

The last relation with allowance for the explicit expression (6) constitutes the complete solution to the problem in the considered model of optical breakdown. It allows the computation of the threshold q_0 for optical breakdown in a gas for any values of the experimentally measurable parameters.

Figure 2 shows the constant-magnetic-field strength dependence, computed from the formulas (6) and (7), of the threshold for CO_2-laser-radiation-induced optical breakdown in helium gas at pressures of 1 and 0.1 atm. We assumed for the parameters the following values: $\tau = 10^{-7}$ sec, $r_0 = 5 \times 10^{-3}$ cm, $l_0 = 2 \times 10^{-2}$ cm, and $l_0 = 5 \times 10^{-2}$ cm.

The adiabatic approximation is valid for $l_0 \gg r_0$, and therefore for $l_0 \sim r_0$ the quantitative results should be regarded as approximate results. Nevertheless, for a slightly diverging radiation focused by a long-focus lens we can expect a lowering in strong magnetic fields of the breakdown threshold by more than ten times at gas pressures $p \ll 1$ atm.

In the experiments[4,5] performed by Cohn et al., the dimensions of the focal region and the radiation intensity were not measured; therefore, the quantitative comparison of the experimental data with the results obtained with the aid of the formulas (6) and (7) presupposes an arbitrary specification of several quantities (q_0, r_0, l_0, $\ln(\alpha^*/\alpha_0)$). Any attempt to estimate the dimensions of the focal region can be considered to be a fitting of the numerous free parameters that secures the subsequent agreement of the results. It may only be noted that for any reasonable values of the parameters the curves $p = p(H)$ constructed from the formulas (6) and (7) coincide in shape with the experimentally obtained curves[4].

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[1)]The breakdown condition was assumed in [4] to be the equality of the rate of ionization of the atoms by electron impact and the rate of diffusion of electrons out of the focal region.

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