Laser-induced breakdown in air in a constant electric field

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An explanation is given of the observed dependence of the threshold for the optical breakdown in air on the electric field. The development of the electron cascade in the focal volume is discussed with allowance for drift escape and Joule heating of electrons in the constant electric field.

In a recent paper Tulip and Seguin[1] reported a change in the threshold for optical breakdown in air when a constant electric field was applied to the gas. The breakdown was produced in a low-pressure chamber placed inside the cavity of a CO_2 laser when the radiation was focused by a lens in the space between two plane-parallel electrodes. The measured dependence of breakdown probability on the constant electric field at constant laser radiation intensity takes the form of a curve with a minimum. It follows that there is a range of electric fields in which the development of the optical breakdown is impeded by the presence of the electric field.

The aim of this note is to explain the observed dependence of the breakdown threshold on the constant electric field. It turns out that this can readily be done if, in the cascade description of the optical breakdown, we additionally take into account the escape of electrons from the focal region, their heating by the constant electric field, and the electrical breakdown. The electron drift velocity U in the constant electric field is proportional to the field strength E, and the Joule heating of the electrons is proportional to E^2. Hence, as E increases, the optical breakdown threshold at first increases, due to the drift escape of electrons from the focal volume, and then begins to fall because, in a sufficiently strong constant electric field, the Joule heating of electrons more readily facilitates the development of the cascade than it prevents the drift escape of electrons. In strong constant fields, the investigation of optical breakdown is restricted by electrical breakdown between the plane electrodes. The threshold E^* for the electrical breakdown is governed by pressure and the properties of the gas.

Optical breakdown by CO_2 laser radiation can only have the cascade character because the quantum of radiation $\hbar\omega$ is too small for the multiphoton ionization of the molecules. The necessary condition for the development of the electron cascade is the presence of initial 'nucleating' electrons. The mechanism responsible for their appearance will be discussed below.

These initial electrons are heated in the radiation field and the constant electric field, and those with energy $\epsilon > I$ (where I is the ionization potential) ionize the gas molecules. The rate of change in the temperatures of the electron is given by

$$\frac{3}{2}n\frac{\partial T}{\partial t}=\tilde{\sigma}\tilde{E}^2+\sigma E^2-I\nu_i n. \qquad (1)$$

In this expression $n(r, t)$ and $T(r, t)$ are, respectively, the density and temperature of the electron, $\tilde{E}$ and E are the alternating and constant electric fields, $\tilde{\sigma}$ and σ are the conductivities of the plasma in the alternating and constant electric fields, which are given by

$$\sigma=\frac{e^2n}{m\nu_{el}},\quad \tilde{\sigma}=\sigma\frac{\nu_{el}^2}{\omega^2+\nu_{el}^2}; \qquad (2)$$

and ν_{el} is the frequency of elastic electron-molecule collisions. The measurements reported in[1] were performed at pressures of 6 and 20 Torr and, therefore, $\nu_{el}^2 \ll \omega^2$. The elastic energy losses are then negligible and the amplitude of the electron oscillations in the light field is much less than the mean free path, so that the conductivity has the simple form given by (2). The ionization frequency ν_i is an exponential function of $-I/T$ (see, for example,[2]), so that the electron temperature increases only up to a certain value after which the entire energy taken up by the electrons in the field is lost through ionization, and the cascade develops practically at constant temperature. The dependence of temperature on the electric field is logarithmic, and in the field strength range which we are considering it follows from (1) that $T = 3$ eV.

Equation (1) does not contain terms describing electron energy losses through excitation of atoms and, therefore, the above temperature is somewhat too low. It cannot be improved because, after a series of breakdowns in air, the chamber contains a mixture of atoms and molecules whose quantitative composition and electron-impact excitation cross sections are not known. However, the above simplifications are not fundamental, and this is in fact confirmed by the agreement between these results and the experimental data.

The electron density in the focal volume is given by the continuity equation

$$\frac{\partial n}{\partial t}+\operatorname{div}\mathbf{j}=\left(\nu_i-\frac{D}{\Lambda^2}\right)n. \qquad (3)$$

In this expression $\mathbf{j}$ is the electron current in a constant electric field:

$$\mathbf{j}=\sigma\mathbf{E}/e=e\mathbf{E}n/m\nu_{el}=n\mathbf{U}.$$

The right-hand side of (3) contains the electron source $\nu_i n$ and the electron sink $-Dn/\Lambda^2$, which effectively takes into account diffusion losses of electrons from the focal volume (D is the electron diffusion coefficient and Λ is the diffusion length).

We can now introduce a cartesian set of coordinates with the Y axis along the constant electric field and the Z axis along the laser beam, so that the $y = 0$ plane touches the cylindrical focal volume. The segment $(0, d_0)$ along the Y axis is illuminated by the laser radiation (d_0 is the diameter of the focal spot).

The electrons drifting through the focal volume along the electric field experience different numbers of ionizing collisions near the Y axis and at large distances from it, and provide different contributions to the development of the cascade. However, the shape and size of the focal region and the distribution of intensity in the focal spot were not measured in the experiment described in[1]. However, for the sake of simplicity, we shall solve the problem for the electron density averaged over the coordinates x and z within the limits of the focal volume. In this way we lose a factor of the order of unity in (6) (see below) which would be present in the final result given by (10) as part of the argument of the logarithm.

With the above averaging, the boundary condition for (3)

$$n(0,t)=n_0 \qquad (4)$$

describes the transport of cascade electrons from the $y = 0$ plane into the focal region by the constant electric field, and the arrival of the initial electrons which replace them. When $t = 0$, the focal volume contains the following initial electron density:

$$n(y,0)=n_0. \qquad (5)$$

The solution of (3)—(5) has the form

$$n(y,t)=\begin{cases} n_0\exp(\nu_i-D/\Lambda^2)y/U, & y\leqslant Ut \\ n_0\exp(\nu_i-D/\Lambda^2)t, & y\geqslant Ut \end{cases}, \qquad (6)$$

and describes the distribution of electron density in the focal volume, averaged over x and z.

If the length τ_l of the laser pulse is less than the transit time $\tau_t = d_0/U$, the electron density reaches the value

$$n(y,\tau_l)=n_0\exp(\nu_i-D/\Lambda^2)\tau_l, \quad U\tau_l\leqslant y\leqslant d_0,$$

and if $\tau_l > \tau_t$ the electron density reaches the maximum value for $y = d_0$

$$n(d_0,t)=n_0\exp(\nu_i-D/\Lambda^2)\tau_t.$$

Combining these expressions we have

$$n^{max}=n_0\exp(\nu_i-D/\Lambda^2)\tau, \quad \tau=\min(\tau_l,\tau_t). \qquad (7)$$

The question of the initial (nucleating) electrons has frequently been discussed in the literature (see, for example,[3]). In the case of lasers with $\hbar\omega \gtrsim 1$ eV, the initial electrons are formed probably during the multiphoton photoionization of impurities with low ionization potentials, but if the photon has $\hbar\omega \ll 1$ eV, the source of the initial electrons is different. We know[4] that, for the first breakdown in a fresh portion of gas, the threshold is much higher than after multiple breakdowns. However, after the first breakdown the threshold is reduced to the previous value, even if the interval between measurements exceeds one hour. This effect is explained by the ionization "quenching"[5] during the spherical spreading of the recombining plasma, i.e., by the appearance of electron concentration which is independent of time but is determined by the initial number of particles and the size and shape of the initial distribution. In the experiment described in[1] the electric field was high enough to produce breakdown in air without the laser radiation, and therefore the presence of the initial electron density can be explained by the ionization "quenching" produced during the electric breakdown.

The condition for optical breakdown is that a certain definite electron density must be reached,[6,7] namely,

$$\alpha^*=n^*/n_a\sim10^{-3}.$$

It follows from (7) that the ionization frequency at breakdown is

$$\nu_i=\frac{1}{\tau}\ln\frac{n^*}{n_0}+\frac{D}{\Lambda^2}. \qquad (8)$$

If we eliminate ν_i from (1) and (7), we obtain the following expression for the breakdown threshold:

$$\tilde{E}=\frac{\omega}{\nu_{el}}\left[\frac{\mathrm{Im}\,\nu_{el}}{e^2}\left(\tau^{-1}\ln\frac{n^*}{n_0}+\frac{D}{\Lambda^2}\right)-E^2\right]^{1/2}. \qquad (9)$$

Under the experimental conditions (see[1]) the laser pulse length was about 200 nsec, the Gaussian diameter of the focal spot calculated for the fundamental mode was $d \approx 0.01$ cm, but the generation regime was multimode and, therefore, in the numerical estimates we assume that $d_0 = 0.04$ cm, $\Lambda = 0.003$ cm, which is not inconsistent with the experiment.[1] In these expressions, d_0 is the effective diameter of the focal spot, since the electron density $n(x, y, z, t)$ was averaged over x and z within the focal volume. At pressures of 6 and 20 Torr, at which the experiment was performed,

$$\tau_l^{-1}\ln\frac{n^*}{n_0}\ll\frac{D}{\Lambda^2},$$

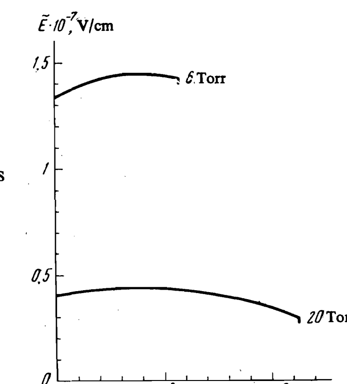
and, therefore, the breakdown threshold for $\tau = \tau_l$ is determined only by diffusion losses. Moreover, $\tau = \tau_l$ only for weak fields $0 \le E \lesssim 10$ v/cm where the constant field has still very little effect on the threshold. For the main range, $10 \lesssim E \le 2000$ V/cm, we have $\tau = \tau_t < 200$ nsec, and it follows from (9) that

$$\tilde{E}=\frac{\omega}{\nu_{el}}\left(\frac{\mathrm{Im}\,\nu_{el}D}{e^2\Lambda^2}+\frac{IE}{ed_0}\ln\frac{n^*}{n_0}-E^2\right)^{1/2}. \qquad (10)$$

Therefore, as the electric field increases, the breakdown threshold at first increases, then passes through a maximum, and eventually monotonically decreases, but before it reaches zero, electric breakdown of air between the electrodes takes place. This value of the electric field (E^*) corresponds to the break on the curve in the figure. The increase in the threshold is explained by the transport of electrons by the constant field out of the focal volume, and the reduction by the heating of the electrons by the field E.

Direct comparison of (10) with the results of the experiment described in[1] is impossible because the measurements were made on the breakdown probability (number of breakdowns per 100 pulses) and not the threshold. The intensity was not varied. Nevertheless, all the comparisons which can be performed suggest that there is good agreement between the results.

The breakdown probability for $p = 20$ Torr becomes zero for 600—800 V/cm, i.e., at the point where the curve for 20 Torr has a maximum. This corresponds to the absence among the 100 pulses of a pulse which would exceed the mean value by 8% in the electric field. The probability of breakdown is unity for $E = 0$ and $E = 2000$ V/cm. The diffusion threshold on the curve for 20 Torr is equal to the breakdown threshold for



Optical breakdown threshold as a function of the constant electric field.

E = 1500 V/cm. The electrical breakdown at 20 Torr occurs for E^* = 2260 V/cm (see[8]). For p = 6 Torr, the breakdown probability is unity when E = 1000 V/cm, and the electric breakdown occurs at E^* = 1160 V/cm. Simultaneous breakdown by radiation and the constant field becomes certain for E = 1000 V/cm, and the rapid reduction in the breakdown probability to zero for E = 800 V/cm corresponds to a small probability of exceeding the mean intensity by an amount sufficient for breakdown at 800 V/cm. The breakdown probability is zero for E = 800 V/cm independently of the value of p, in complete agreement with (10). No other comparison with the experiment[1] can be performed, but certain predictions can be made.

All the $\tilde{E} = \tilde{E}(E)$ curves have a maximum at

$$E=\frac{I}{2ed_0}\ln\frac{n^*}{n_0}.$$

For pressures p > 30 Torr (for the other conditions see[1]), as E increases beyond 1000 V/cm, the threshold for optical breakdown will fall substantially before the combined optical and electrical breakdown takes place. For p ~ 1 Torr, the electric breakdown occurs for E^* ~ 700 V/cm, and the electric field will increase the optical threshold by only a few per cent. For p < 1 Torr, E^* increases with decreasing p, and the optical breakdown threshold decreases with increasing E > 800 V/cm.

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