CASCADE IONIZATION OF GAS IN A HIGH-INTENSITY LIGHT FIELD

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1. The Zel'dovich and Raizer theory of optical gas breakdown under the influence of laser emission [1] corresponds to the condition of relatively low rate of energy accumulation by the electron in the field of the electromagnetic wave:

$$\epsilon_0 \sigma_{tr} < I\sigma_i. \tag{1}$$

Here $\epsilon_0 = e^2E^2/2m\omega^2$ is the effective oscillation energy of an electron with charge e and mass m in the field of a wave with amplitude E_0 and frequency ω, and σ_{tr} and σ_i are respectively the transport cross section of elastic electron-atom collisions and the ionization cross section of atoms with ionization potential I. When the pulse duration T is decreased, the threshold flux density $q = cE_0^2/8\pi$ in the theory [1] increases in proportion to $1/T$. Thus, condition (1) is violated if the pulse duration is sufficiently small.

If

$$\eta = \frac{\epsilon_0 \sigma_{tr}}{I\sigma_i} > 1 \tag{2}$$

the picture of the breakdown is radically altered.

When inequality (2) is satisfied, the electrons acquire during the time between two inelastic collisions an energy ϵ greatly in excess of the ionization potential I. This means that in the energy space the trajectory of the electron produced as a result of the inelastic collision is determined by the formula

$$\frac{d\epsilon}{dt} = \alpha(\epsilon), \tag{3}$$

where $\alpha(\epsilon) = \epsilon_0 N_0 \sigma_{tr}(\tau)v$, v is the electron velocity, and N_0 is the atom density.

Assuming that the electrons produced as a result of the ionization have an initial energy $\epsilon \ll \epsilon_0$, we can write for the distribution function $f(\epsilon, t)$, at $\epsilon > \epsilon_0$, the kinetic equation

$$\frac{\partial f}{\partial t} + \frac{\partial}{\partial \epsilon}(\alpha(\epsilon) f) = 0. \tag{4}$$

The solution of (4) is conveniently written in the form

$$f(\epsilon, t) = \frac{\alpha(\epsilon(\tau_0))}{\alpha(\epsilon)} F\left(t - \int_0^{\epsilon} \frac{d\epsilon'}{\alpha(\epsilon')}\right), \tag{5}$$

where $F(\tau)$ is an arbitrary function of $\tau = t - \int_0^{\epsilon} d\epsilon'/\alpha(\epsilon') \gtrsim 0$, τ_0 is the time of ionization of the atom by an electron with zero initial energy, and $\epsilon(\tau_0)$ is the energy acquired by the electron within the time τ_0. $F(\tau)$ can be determined from an integral equation corresponding to the cascade-development model assumed by us:

$$F(\tau) = \int_0^{\epsilon(\tau)} F\left(\tau - \int_0^{\epsilon} \frac{d\epsilon'}{a(\epsilon')} N_0 \sigma_i(\epsilon) v \frac{d\epsilon}{a(\epsilon)}\right). \quad (6)$$

Indeed, equating the number of electrons in the energy interval from ϵ to $\epsilon + d\epsilon$ at the instant of time t to the number of electrons produced as a result of ionization during the time interval from $\tau + d\tau$ to τ, we obtain (6). The solution (6) can be represented in the form

$$F(\tau) = F_0 e^{\gamma\tau}, \quad (7)$$

where $F_0 = n_0/\tau_0 \alpha(\epsilon(\tau_0))$ is a normalization function that takes into account the contribution of the bare electrons n_0 to f. Substituting (7) in (6) and setting the upper limit of integration equal to infinity, we obtain an equation for the cascade-development constant γ:

$$N_0 \sqrt{\frac{2}{m}} \int_0^{\infty} \exp\left\{-\gamma \int_0^{\epsilon} \frac{d\epsilon'}{a(\epsilon')}\right\} \frac{\sigma(\epsilon)\sqrt{\epsilon}\, d\epsilon}{a(\epsilon)} = 1. \quad (8)$$

In particular, when $\alpha(\epsilon)$ is constant and σ_i decreases at high energies like $1/\epsilon$ [2], the electron density $n(t) = \int_0^{\infty} f(\epsilon, t) d\epsilon$, the average electron energy $\bar{\epsilon}(t) = 1/n(t) \int_0^{\infty} f(\epsilon, t) \epsilon \, d\epsilon$, and the laser-emission absorption coefficient $k(t)$ are respectively equal to

$$n(t) = \frac{n_0}{\tau_0 \gamma} e^{\gamma t}, \quad \bar{\epsilon}(t) = \frac{a}{\gamma}, \quad k(t) = \frac{a n_0}{q \gamma \tau_0} e^{\gamma t}, \quad (9)$$

and the cascade-development constant γ is connected with the quantity α, with the neutral-atom concentration N_0, and with the maximum ionization cross section $\sigma_{im} = \sigma_i(\epsilon_m)$ by the relation

$$\gamma = \frac{2\pi}{am} N_0^2 \epsilon_m^2 \sigma_{im}^2. \quad (10)$$

In the indicated case, the cascade-development time $\theta = 1/\gamma$ is proportional to the radiation flux density q, the electron concentration at a fixed value of the time decreases with increasing q, and the average electron energy does not depend on the time and increases in proportion to q^2.

The applicability of this mechanism of ionization is limited from below by the condition (1), and from above by the photoionization in the strong field [3]. For example, for a neodymium laser pulse with $T = 5 \times 10^{-12}$ sec, $N_0 = 10^{19}$ cm^{-3}, and $I = 20$ eV the flux-density range amounts to $\sigma_i/\sigma_{tr} 10^{14} < q < 10^{15}$ W/cm.

[1] Ya. B. Zel'dovich and Yu. P. Raizer, Zh. Eksp. Teor. Fiz. 47, 1150 (1964) [Sov. Phys.-JETP 20, 772 (1965)].

[2] L. D. Landau and E. M. Lifshitz, Kvantovaya mekhanika, Fizmatgiz, 2d ed. 1963 [Quantum Mechanics, Addison-Wesley, 1958].