Similarity principles for laser-induced breakdown in gases

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The well-known similarity principles for dc breakdown in gases are extended to the case of laser-induced breakdown. The wealth of experimental data on kinetic processes in gases may therefore be directly applied to ac breakdown. Without solving the Boltzmann equation, the ionization rate is determined as a function of pressure, frequency, electric field, etc. This has important implications for the maximum possible light intensity in high-pressure TEA amplifiers.

Similarity principles have always played an important role in the study of electric discharges, ionization, and breakdown in gases.[1] For example, it is well known that α, the ionization per unit length, can be written as $\alpha/p=f(E/p)$, where p is the pressure and E is the dc electric field.

Of central importance in this paper is not α but η, the ionization per unit time, to which it is directly related by $\eta=\alpha v$, where v is the drift velocity of the electrons. The ratio η/p also satisfies a scaling law of the form

$$\eta/p=f'(E/p). \qquad (1)$$

The function f' has been measured[2,3] over a wide range of dc electric fields in almost all gases. For laser-induced breakdown we will use the ac generalization of (1):

$$\eta/p=f'[E_{\rm rms}/p(1+\omega^2\tau^2)^{1/2}], \qquad (2)$$

where $E_{\rm rms}$ is the rms ac or dc field, ω is the laser frequency, and τ is the momentum transfer collision time.

The similarity principle (2) has been discussed for microwaves,[4] but it has not been applied to CO_2 laser-induced breakdown, where it is expected to be very useful. On the other hand, for ruby and Nd laser frequencies, which are so high that photoionization from electronically excited states is possible, the scaling law (2) may not be valid.[5] Using (2), the ionization rate η can be determined from the measured dc values of the function f'.

The criterion for laser-induced breakdown is that the electron multiplication number $M\equiv\exp\{\eta T\}$ should be very large, of the order 10^8, i.e., the electric field should be so large that $\eta\approx 18/T$, where T is the laser pulse duration. If the loss rate g of electrons by diffusion is significant, then the threshold is determined by the criterion $\eta-g\approx 18/T$.

The solid line in Fig. 1 shows a plot of the function f' for helium, as determined from dc measurements.[6,7] The dashed line shows the ionization rate given by the formula[8]:

$$\eta=\frac{e^2\tau|E|^2}{I_0 m(1+\omega^2\tau^2)}, \qquad (3)$$

where I_0 is the ionization potential, and e and m are the electronic charge and mass, respectively. Equation (3), which is based on the simplistic assumption that all the absorbed energy results in ionization, has been used in analyzing most of the CO_2 laser-induced breakdown experiments[9-11] to date. As can be seen from Fig. 1, only a small fraction of the total absorbed energy results in ionization. The crosses are data points taken from Ref. 9 (where uniform preionization was used to

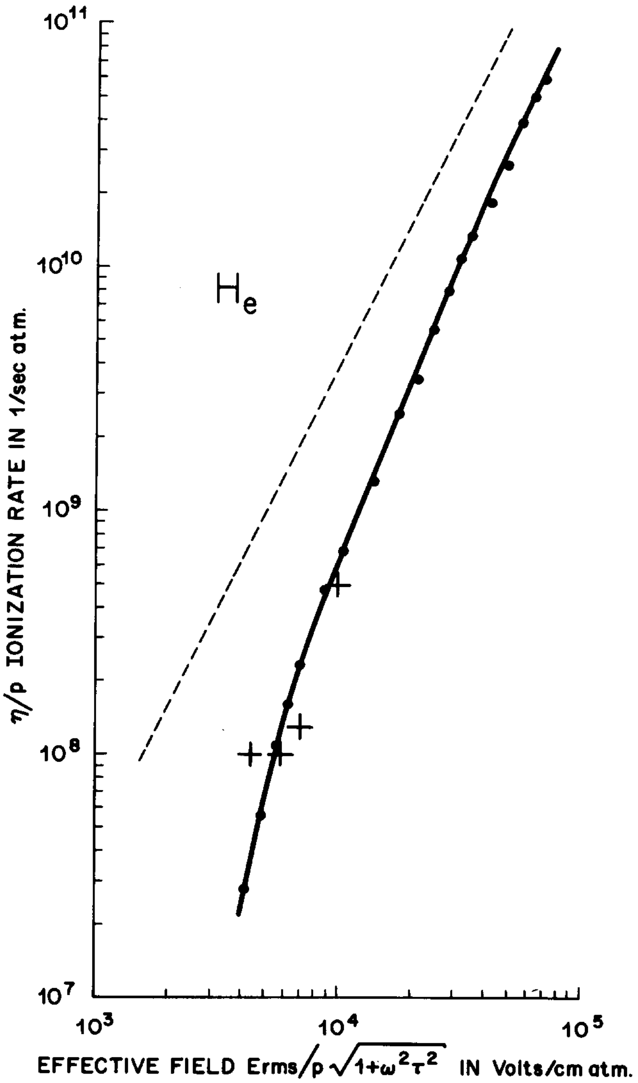

FIG. 1. Ionization rate η/p as a function of the effective electric field $E_{\rm rms}/p(1+\omega^2\tau^2)^{1/2}$ for helium. The solid line and the dots are dc data. The crosses are CO_2 laser breakdown data. (For He at 1 atm, $\omega\tau=103$). The similarity principle states that the dc and the ac data should agree. The dashed line is a simple theory which has been used previously.

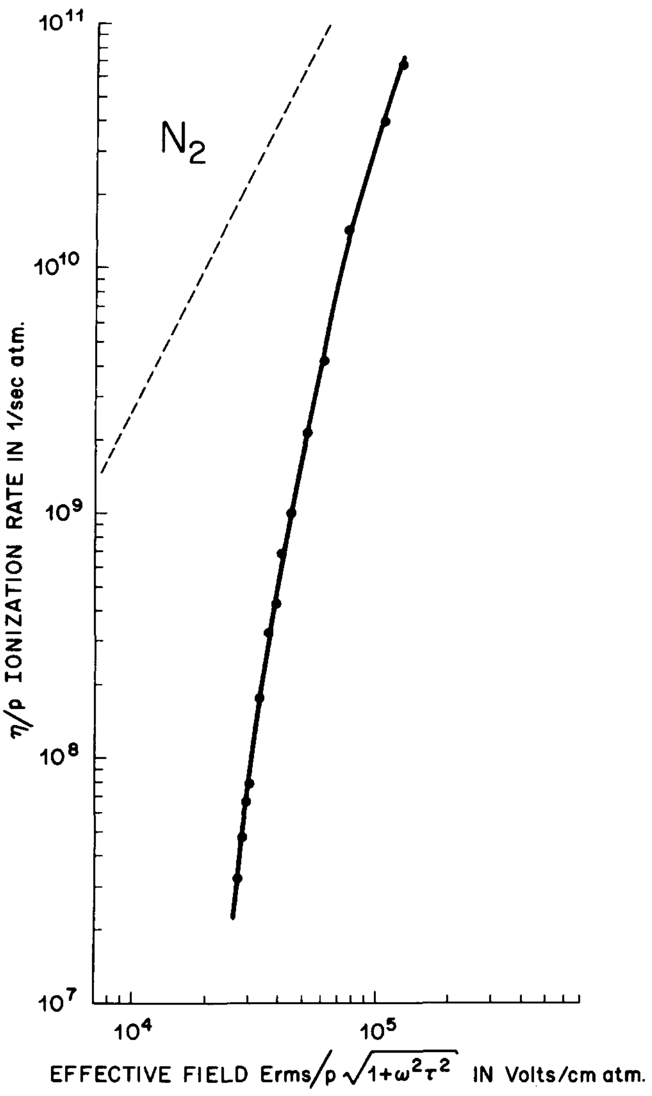

FIG. 2. Ionization rate η/p as a function of the effective electric field $E_{\text{rms}}/p(1+\omega^2\tau^2)^{1/2}$. The solid line and dots are dc data. The universal curve may be used to scale to various electric fields, pressures, and frequencies (for N_2 at 1 atm, $\omega\tau = 40$). Notice that η is a sensitive function of electric field. The dashed line is a simple theory which has been used previously.

resolve the ambiguity of the source of the initial avalanche electron). The loss rate of electrons by diffusion was approximated by the standard formula $g = 2\langle\mathcal{E}\rangle\tau/3m\Lambda^2$, where Λ is the characteristic diffusion length and $\langle\mathcal{E}\rangle$, the mean energy, was taken as $I_0/3$. It should be remembered that $\omega\tau = 103$ for He at 1 atm.[12]

As can be seen, the agreement with experiment is reasonable; however, the main importance of Fig. 1 is that the universal curve can be used to predict the pressure, frequency, and pulse length dependence of the laser-induced breakdown in regimes which have not yet been directly studied.

Figure 2 presents f' for nitrogen.[13] Even a smaller fraction of the absorbed energy goes into ionization in nitrogen than in helium, the remainder probably ending as electronic excitation.[14] Notice also that the ionization rate is a very sensitive function of electric field, a characteristic of most gases. Since $\partial\ln\eta/\partial\ln E > 2$, the breakdown does not become energy flux dependent, but remains a function of both intensity and pulse length, even for laser pulses as short as 1 nsec, contrary to some previous predictions. The curve indicates that it will probably not be possible to exceed 10^{10}/W/cm^2 in a TEA CO_2 amplifier even for very short pulses.[11] Since the denominator $p(1+\omega^2)^{1/2}$, is independent of pressure in the high-frequency limit, the breakdown field will not depend very sensitively on pressure in the absence of diffusive effects. (Note also that $\omega\tau = 40$ at 1 atm of nitrogen.[15,16])

The similarity principle (2) can be derived from the Boltzmann equation which is normally used in these problems.[14] Diffusion must be treated separately, and three-body collisions should, of course, be ignored. The scaling law is exact if the momentum transfer collision time τ is essentially independent of electron energy in the important range between 1 eV and the ionization potential, a condition which is reasonably satisfied in many gases. Otherwise, an average value of the collision time τ must be used, and the scaling law is only approximate.[4]

We believe we have shown the applicability of similarity principles to laser-induced breakdown. The author acknowledges a useful discussion with D.C. Smith.

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