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3.1 Low Pressure Discharges (here breakdown process in low pressure gas)

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We describe here a study of the formative time of gas breakdown in an electric field at right angles to a very strong uniform static magnetic field. This means the latter is parallel to the essentially plane parallel electrodes, and is so large that the electron gyrofrequency ω is always much greater than the electron collision frequency ($\omega \gg \nu$). The electric field is pulsed-on to a value well above breakdown threshold. In fact, the applied voltage is generally selected high enough that the formative time turns out to be shorter than the time taken by an electron to drift from the cathode all the way to the anode. This means the breakdown is accomplished essentially by the primary electron avalanches alone, and the effect of secondary electrons released at the cathode can in a first approximation be neglected. The resulting simplifications permit theoretical predictions for the breakdown time as a function of the fields and the gas density; these predictions are based on extrapolated values of observed or computed ionization rates and drfit speeds. The fair agreement between observed and predicted formative times may then be taken as a partial confirmation of our theoretical notions.

1. THEORY

The electron velocity distribution function in a gas in uniform, static, orthogonal, electric (E) and magnetic (B) fields is expected to be a function of the ratio E/B only, provided that $\omega \gg \nu$ and that the $E \times B$ drift speed is not relativistic [1]. Here $\omega = eB/m$ is the electron gyrofrequency, and ν denotes the electrons mean collision frequency for momentum transfer averaged over all collisions, regardless of whether they are elastic or inelastic. This fact can of course be derived from a complete analysis of electron dynamics such as described by Allis [2], but it is readily understood with the help of a simple physical argument.

If $\omega \gg \nu$ practically all electrons, regardless of their random motion, participate in a uniform drift very nearly given by

$$\vec{v}_d \equiv \vec{E} \times \vec{B}/B^2. \tag{1}$$

The drift along $-\vec{E}$ is very much smaller, its magnitude being approximately given by $v_E \approx v_d \nu/\omega$. In a frame of reference moving with velocity $\vec{v}_d$ through the gas, the electric field is exactly zero. Thus when viewed in this "drift frame", the energy gain of the electrons cannot be ascribed to an electric field at all but must be considered as being caused by impacts of the electrons with the gas molecules, which in this frame are moving through the gyrating electrons with a wind velocity $-\vec{v}_d$. Neither B nor E enter separately into the process as long as v_E can be neglected when compared with v_d. Likewise, the gas pressure does not affect the velocity distribution in this limit, even if ν is admitted to be a function of velocity, since all collisions are proportional to the gas density.

It follows that the ionization rate [here denoted by β] is expected to be proportional to the gas density and otherwise a function of E/B only. This is in agreement with the "effective pressure" concept $p_{eff} = p(1 + \omega^2/\nu^2)^{1/2}$, introduced by Blevin and Haydon [3] to describe the relation between α/p and E/p in orthoganal fields for the constant-collision-frequency approximation. In the strong-field limit, $p_{eff} \propto B$ and the gas density cancels out, so that we now expect α/B to be a function of E/B. Substituting our expression for v_E we obtain indeed

$$\beta \equiv \alpha v_E = n_g F(E/B) \tag{2}$$

where n_g is the gas density. More specifically, based on extrapolations of experimental determinations of α [4], [5] and v_E[6] and supported by numerical computations of β [7], an approximate quantitative expression for hydrogen is

$$\beta/n_g = 2.6 \times 10^{-8}(E/B)\ \exp(-0.78B/E)\ \text{cm}^3/\text{sec}, \tag{3}$$

where B is expressed in gauss and E in volt/cm.

As indicated in Fig. 1, for the purpose of this discussion the formative time T_B is defined as the interval between the instant the applied voltage first reaches 85% of its full value and the point in time when a marked voltage decrease is discernible. For the circuit used, the latter implies currents in the ampere range, so that electric-field distortions must always have been involved in the process of our "breakdown" regardless of its detailed mechanism and the further development of the discharge. We therefore argue that "breakdown" occurs when a certain avalanche strength is reached, and assume for simplicity that this critical amplification is the same for all fields and pressures used. Our criterion is thus analogous to that for midgap

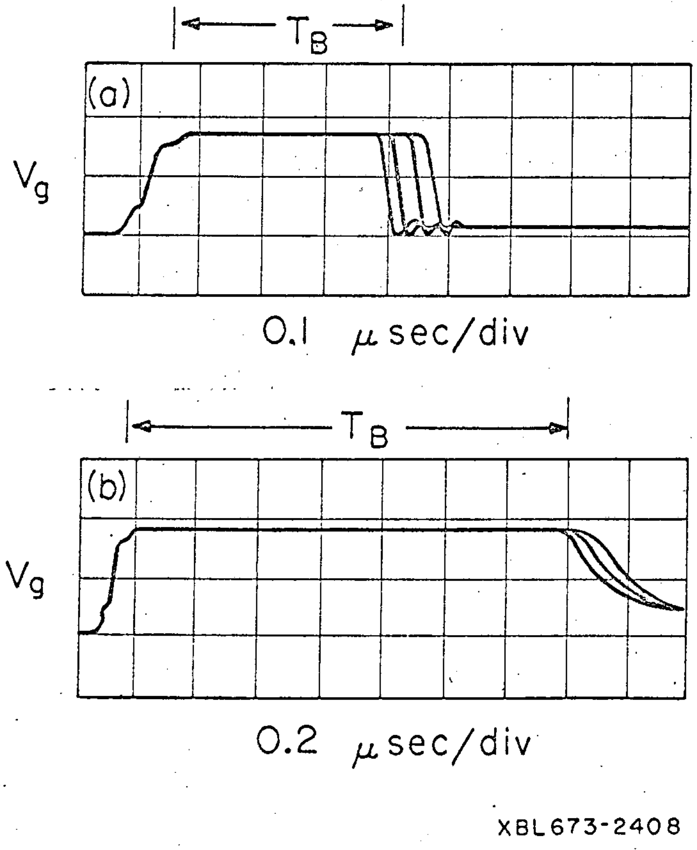

Fig. 1. Typical oscilloscope traces of voltage vs time. (a) 0.8-cm gap; 1.0 torr; 7.2 kV; 18 kG (four trace overlay). (b) 0.8-cm gap; 1.0 torr; 3.6 kV; 18 kG (five trace overlay).

breakdown by the streamer mechanism in the absence of a magnetic field:

$$T_B = (\ln N/N_0)/n_g F(E/B), \qquad (4)$$

where $\ln N/N_0$ must be a number in the neighborhood of 27; the precise value depends on the number of initial electrons present and on their distribution in the gap.

2. EXPERIMENT

As in the previous work by Bernstein [6] our experiment was done with coaxial cylindrical electrodes with gaps (d) much smaller than their radius so that plane parallel configurations were closely approximated. The entire structure was inserted between the pole faces of a large electromagnet and carefully aligned to ensure that the fields were accurately orthogonal. The perturbing effects of electric fringe fields at the ends of the gaps were suppressed by covering the ends with thin glass plates coated on the outside with a resistive paint which adequately graded the potential. The aluminum cathode (inside cylinder), illuminated with uv light through small holes in the anode, provided a substantial but unknown number of initial electrons. The voltage V_g from a dc power supply was applied abruptly via a thyratron tube and a 100-ohm current-limiting resistor. The pressure was varied from 0.2 to 2 torr and the magnetic field from 6 to 18 kG. Three different gap spacings (3, 5, and 8 mm) were tried, and the voltage was chosen to always yield one of three preselected ratios of E/B (shown in Fig. 3). Hydrogen gas was used throughout.

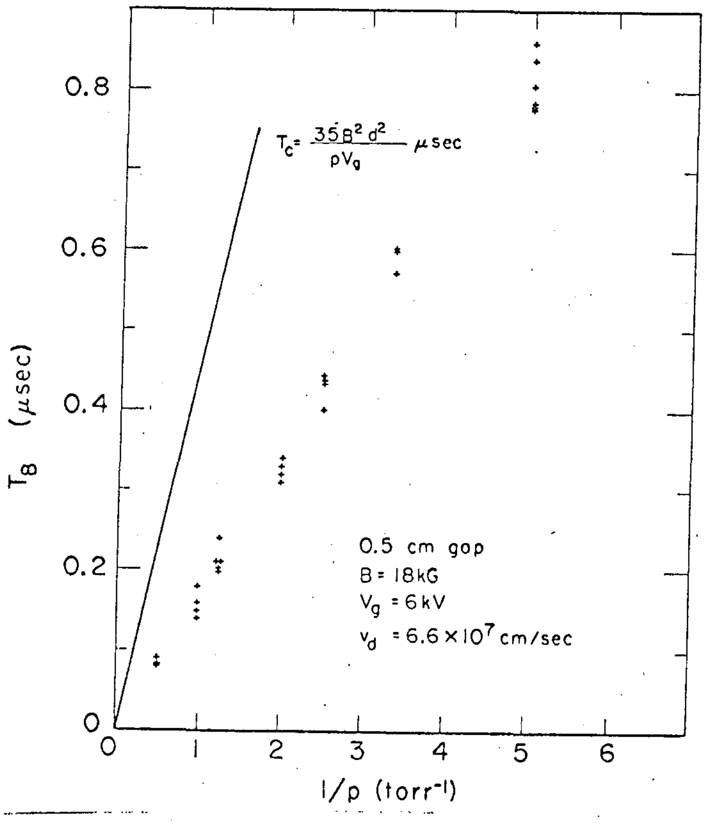

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Fig. 2. Formative time vs 1/p.

A few typical oscilloscope traces are displayed in Fig. 1. The nature of the usual statistical scatter is apparent.

Figure 2 shows a set of formative times plotted against 1/p for given fields and gap spacing. Also indicated is the estimated avalanche crossing time $T_c \equiv d/v_E$. When $T_c > T_B$, the inverse pressure dependence predicted by Eq. (4) is indeed observed. When $T_B > T_c$, i.e., when secondary processes must play a significant role, a nonlinear dependence on 1/p is usually found.

If Eq. (4) is valid, the product $n_g T_B$ should not depend on E, B, or d alone. Figure 3 shows that some direct effect of B (or E) alone is observed, however, and similar deviations, notably at large values of B, occur when the gap spacing d is varied. We have tentatively ascribed these deviations to electron losses at the glass ends, which are of course not included in Eq. (4). Interestingly, the quantitative predictions based on Eq. (3) and indicated by arrows on Fig. 3 are rather satisfactory. (Data marked by the letter m lie above $n_g T_c$.)

We conclude that breakdown occurs after ionization growth by a factor of 10^{12} or more, at which time the electric field evidently is strongly distorted even if the electrons have spread throughout the entire cylindrical gap.

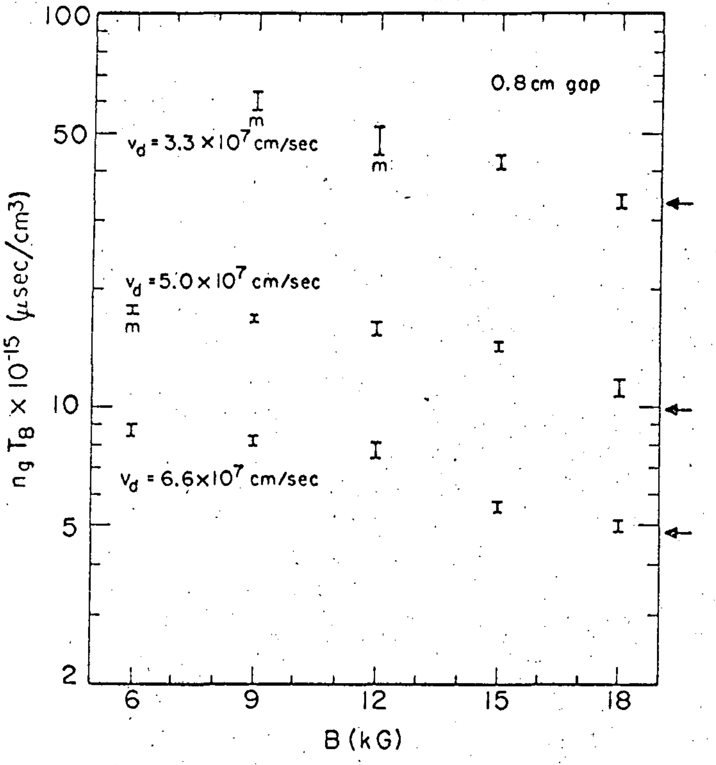

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Fig. 3. Product $n_g T_B$ for various fields.

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