II. MICROWAVE GASEOUS DISCHARGES

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A. PULSED BREAKDOWN

The breakdown field is defined as that field for which the number of electrons produced per second equals the number lost per second through diffusion. Under these conditions, the electron density will build up to a finite value only after an infinite length of time. To make the breakdown occur within a finite time it is necessary to have an over-voltage such that the number of electrons produced per second is greater than the number diffusing per second. Under these conditions, the electron density will build up, slowly at first where free diffusion is the controlling factor, and then more rapidly as the diffusion is inhibited by the building up of a positive ion space charge. The density build-up with space charge is much more rapid than the density build-up without space charge. The controlling factor, therefore, will be the density build-up with free diffusion to a point where positive ion space charge becomes appreciable.

The equations governing the build-up of the electron density are of the form:

$$(\gamma_k + jk\omega - \bar{v}_1^k) \, n_k = \nabla^2 D^k n_k \quad .$$

γ is the rate of build-up of the energy distribution function of the electrons, F_0^k, with time; ω is the angular frequency of the electric field; and $\bar{v}_1^k$ is the average ionization rate defined by

$$\bar{v}_1^k = \frac{1}{n_k} \int v_1 \, F_0^k \, 4\pi r^2 dr \quad .$$

D^k is the free diffusion coefficient for electrons, and n_k is the electron density. Solutions of the diffusion equation will not satisfy the boundary conditions that the electron density go to zero at the walls, unless

$$\gamma_{kp} + j\omega k - \bar{v}_1^k = -\frac{D^k}{\Lambda_p^2} \quad ,$$

where the lengths Λ_p are characteristic of the boundary over which $n = 0$.
The largest characteristic value of γ will be:

$$\gamma_o = \bar{v}_1 - \frac{D}{\Lambda_o^2} \quad .$$

The other solutions will rapidly damp out and γ_o alone will represent the build-up or decay of the distribution. To a first approximation, the electron density as a function of time is given by

$$n = n_o e^{\gamma_o t} \quad ,$$

where n_o is the initial number of electrons present within the cavity. The breakdown condition for the c-w case is $\gamma_o = 0$, but for pulsed cases $\gamma_o > 0$ and

$$n_d = n_o e^{\gamma_o \tau} = n_o e^{(\bar{v}_1 - \frac{D}{\Lambda_o^2})\tau} \quad ,$$

where n_d is the density at which the positive ion space charge becomes predominant, and τ is the pulse width. Under these conditions, the density will build up to n_d within the time τ.

The ionization rate, $\bar{v}_1$, is an increasing function of the electric field E. γ_o may be written

$$\gamma_o = \bar{v}_1 - \bar{v}_{1o} = (\frac{v_1}{D})(\frac{D}{\mu})\mu - (\frac{v_{1o}}{D_o})(\frac{D_o}{\mu})\mu \quad ,$$

where $\bar{v}_{1o}$ is the ionization rate for c-w breakdown, $\bar{v}_1$ is that for pulsed breakdown, and μ is the mobility. In terms of the high frequency ionization coefficient ζ, we may write:

$$\gamma_o = [E^2 \zeta(\frac{E}{p})\frac{D}{\mu}(\frac{E}{p}) - E_o^2 \zeta(\frac{E_o}{p})\frac{D}{\mu}(\frac{E_o}{p})]\mu \quad .$$

By the method outlined in Section II-c, of the R.L.E. Progress Report of July 15, 1949, D/μ as a function of E/p has been determined for hydrogen gas. The results of these measurements are shown in Figure II-1. Experimentally determined values of ζ for hydrogen are shown in Figure II-1 of the R.L.E. Progress Report of October 15, 1948. The mobility of electrons in hydrogen is calculated to be $\mu = 2.97 \times 10^5/p$. The quantity $\ln(n_d/n_o)$ is an adjustable constant and should be a function, to some extent, of the sensitivity of the detecting apparatus. The value used for computing was $\ln(n_d/n_o) = 13.4$ corresponding to $n_d/n_o = 10^6$. The experimental and theoretical curves are shown in Figure II-2. For long pulse widths, the values of the breakdown field approach the c-w values.
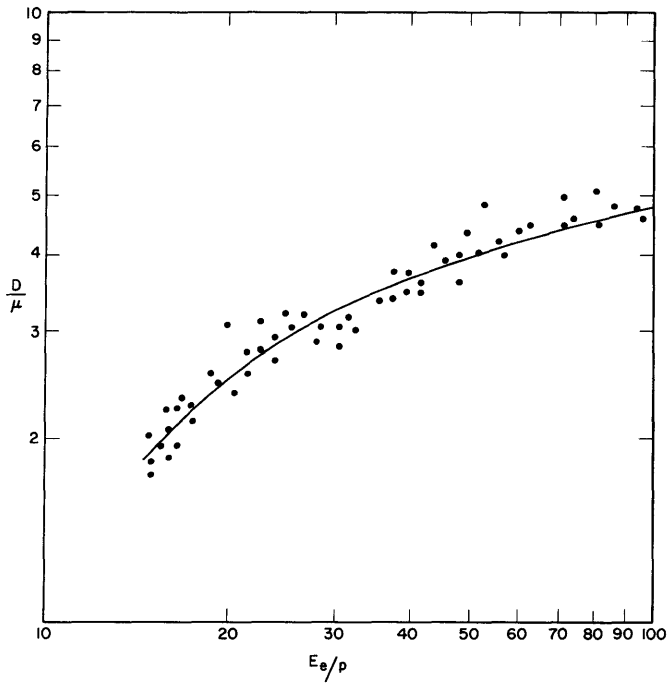
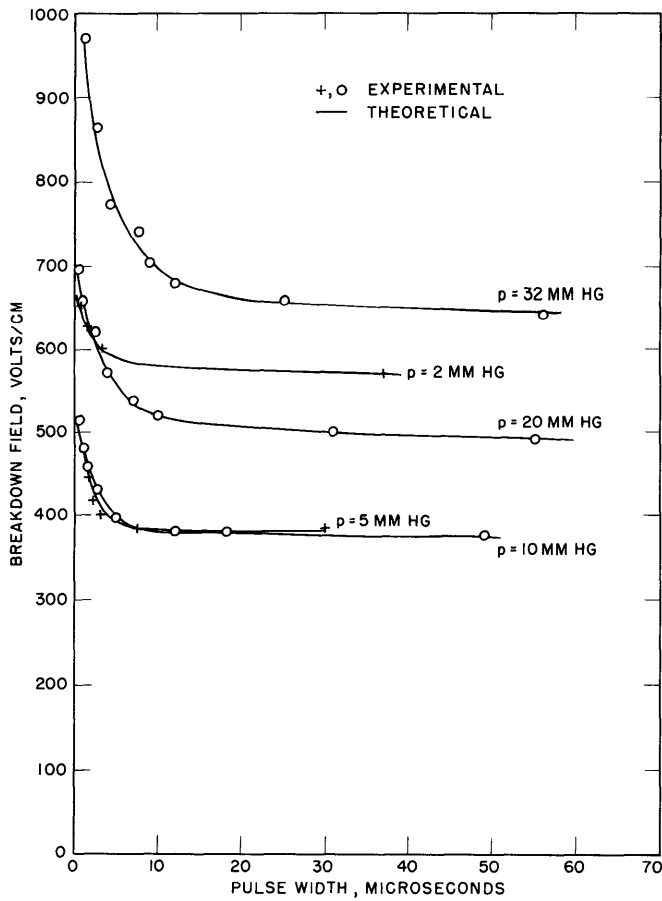Fig. II-1 Experimental values of D/μ as a function of E_e/p for hydrogen gas.

Fig. II-2 Experimental and theoretical breakdown fields for various pressures of hydrogen as a function of pulse width in microseconds.

B. 100-MEGACYCLE CAVITY

To check and extend the predictions of microwave gas discharge break-down to lower frequency studies, a re-entrant cavity at 100 megacycles has been constructed. The necessary auxiliary equipment, such as oscillators and amplifiers, has been constructed, and data will soon be taken.

The cavity measures 42 inches in diameter and 20 inches in height with a re-entrant post 13 inches in diameter and 15 inches in length. The vacuum chamber, 12 inches in diameter and 5 inches in height, completes the cavity. This chamber consists of two 1/4-inch-thick brass plates which are sealed to the ends of a pyrex glass cylinder 12 inches in diameter, 5 inches long, with a wall thickness of 1/2 inch. The rest of the cavity — top, bottom, and sides — is constructed of 1/16-inch copper sheet fastened to a rigid supporting frame.

The vacuum seal is made with Apiezon Q wax covered with Glyptol enamel. After evacuation, the end plates are held to the glass cylinder by the atmospheric pressure only. The chamber pumps to a vacuum of 2 or 3×10^{-7} mm of Hg.

The 100-megacycle, 150-watt power amplifier used to energize the cavity consists of an air-cooled Eimac 4X150A tetrode in a one-quarter wave coaxial line tank circuit. Power is taken from this amplifier by means of an adjustable spring contact on the inner cylinder of the tank circuit. Grid excitation of the amplifier occurs in a similar manner. The primary oscillator is a stabilized 5-megacycle Hartley oscillator with multipliers up to 100 megacycles.

C. POSITIVE ION ANALYSIS

A mass spectrometer is being built for measuring the relative concentrations of the various kinds of positive ions present in a microwave gas discharge and in the plasma during the decay period following the discharge. The spectrometer will be used to determine whether the positive ion mobility calculated from the measured ambipolar diffusion coefficient for helium (1) is that of the atomic ion, He^+, or the molecular ion, He_2^+ (2). It is expected that the spectrometer will also be used to study the electron-positive ion recombination process in the rare gases (3), (4).

The spectrometer is of the 60° deflection type and is provided with a differential pumping system so that the microwave cavity can be operated at pressures in the millimeter range. A preliminary check of the pumping system shows that the pressure in the analyzer tube can be maintained at 10^{-4} mm of Hg with 5 mm pressure of tank helium in the cavity. The

microwave cavity is operated at ground potential so that it is possible to use the frequency-shift method (5) for measuring electron densities while making simultaneous measurements of positive ion concentrations. An Allen-type electron multiplier has been assembled for use as an ion detector. This detector should provide a high sensitivity and allow the measurement of ion concentrations as a function of time.

D. DIELECTRIC COEFFICIENT OF PLASMAS

In the R.L.E. Progress Report of April 15, 1949, a drawing was shown of a discharge tube designed to permit study of the dielectric properties of a discharge. Difficulties have been encountered with this tube because of vacuum leaks and undesired high-order transverse electric waves.

The original design called for vacuum windows made of Teflon 0.018 inch thick, but pumping tests and microscopic examination reveal that the Teflon contains minute imperfections that render it unsuitable for the purpose. The design has been altered to accommodate a combination window of mica and Teflon. The mica, with a lead foil gasket, is used to give the vacuum seal, and the Teflon is retained to control the wavelength in the radial-line r-f chokes at each end of the tube.

Because the average diameter of the transmission line is about one wavelength, Te_{on} modes are allowed for n as large as three. Elimination of these waves requires that very close tolerances be maintained on concentricity and on the circular shape of the cylinders forming the line. It has been necessary to add several strengthening members to maintain these tolerances and at the same time to aid in the vacuum seal problem.

A cathode-heater design has been worked out and tested to insure proper cathode operating temperature in the presence of cooling loss from helium and hydrogen at pressures up to about 20 mm Hg.

References

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