

II. MICROWAVE GASEOUS DISCHARGES

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A. 100-MEGACYCLE BREAKDOWN

Previous studies (1, 2) of microwave breakdown in hydrogen have led to a very successful theoretical explanation for the behavior of the phenomenon of a-c breakdown. The theory was applied not only to the 10-centimeter wavelength observations carried out in this laboratory, but also to longer wavelength measurements of others. The 100-Mc cavity was designed to extend the range of the experimental observations with the knowledge that the theory would also have to be modified since the range of the previous theory in the direction of higher pressure had already been reached.

A new theory has been developed for the radio frequency breakdown of a discharge in hydrogen which is applicable to the higher pressure phenomena. At higher pressures, the energy per mean free path which the electrons gain in the field is low, and the electron gains energy almost entirely by elastic collision. A much simpler theory has been developed for this case which is applicable at high pressure breakdown at the lower frequencies calculated by the previous theory so that the two theories can be shown to overlap.

The velocity distribution of electrons in a discharge simplifies considerably when the assumptions are made that the diffusion does not affect the energy, and the elastic collision frequency ν_c is constant with energy. These conditions hold for breakdown in hydrogen over a wide range of the experimental parameters and it has been possible to derive a relatively simple formula to calculate the breakdown condition.

Under the above assumptions the energy distribution function below the excitation potential u_x is given by

$$f_o = \frac{\bar{\nu}_x + \bar{\nu}_i}{4\pi\nu_c} \frac{M}{mu_E} e^{-u/u_E} \int_u^{u_o} \frac{e^{u/u_E}}{v^3} du \quad (1)$$

where u is the energy of the electron in electron-volts

$$u_E = \frac{M}{3m} \frac{e}{m} \frac{E^2}{\nu_c + \omega^2} \quad (2)$$

and u_o is the "overshoot energy", about 2 volts above the first excitation potential.

The distribution function is used to calculate the diffusion coefficient

$$D = \int_0^{v_o} \frac{v^2}{3\nu_c} f_o 4\pi v^2 dv \quad (3)$$

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This is introduced in the breakdown condition

$$D = \Lambda^2 \bar{\nu}_i \quad (4)$$

to give, after an integration by parts,

$$\frac{\bar{\nu}_i}{\bar{\nu}_x + \bar{\nu}_i} = \left(\frac{u_0}{E\Lambda}\right)^2 \frac{\nu_c^2 + \omega^2}{\nu_c^2} \frac{1}{5} V\left(\frac{u_0}{u_E}\right) \quad (5)$$

The function V is defined by

$$V(w) = \frac{5}{w} \left[\frac{3}{2w} \int_0^w \sqrt{x} e^{-x} \int_x^w \frac{e^y}{y^{3/2}} dy dx - 1 \right] \quad (6)$$

This function has been computed by the Joint Computing Group of the Massachusetts Institute of Technology.

To calculate the ionization fraction $\bar{\nu}_i/(\bar{\nu}_x + \bar{\nu}_i)$ it is necessary to know that part of the distribution function which lies above the excitation potential. This can be calculated from the experimental excitation and ionization probabilities, but if the problem is attacked in this way the mathematics becomes exceedingly cumbersome. It is better to assume a mathematically convenient distribution function containing adjustable parameters. The assumed excitation probability is chosen to be a good approximation of the experimental excitation probability. Two parameters, a and b, have been found to be sufficient, and the assumed function is

$$f_0 = Au^{b-1/2} e^{-au} \quad (7)$$

This corresponds to the inelastic ratio

$$\frac{M}{2m} \frac{\nu_x + \nu_i}{\nu_c} = (au_E - 1) au + b + 1 - (2b + 1/2) au_E + b(b - 1/2) \frac{u_E}{u} \quad (8)$$

In this formula ν_x and ν_i are the excitation and ionization frequencies for electrons of a given energy, whereas $\bar{\nu}_x$ and $\bar{\nu}_i$ are the average values per electron in the discharge. The parameters a and b are now chosen, for each value of E/p, so that the inelastic fraction is correct, in value and slope, at the excitation potential.

The ionization ratio is given by

$$\frac{M}{2m} \frac{\nu_i}{\nu_c} = h_i (u - u_i) \quad (9)$$

where h_i is an experimental constant. As $\frac{2m}{M} u_i \nu_c$ is the power loss to recoil per electron, this is the ratio of the energy loss to ionization to the energy loss to recoil. Using this and the assumed distribution function one obtains the ionization fraction

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$$\frac{\bar{v}_i}{\bar{v}_x + \bar{v}_i} = \frac{h_i}{a^2 u_E} \frac{S}{a u_o - \frac{u_o}{u_E} - b + \frac{1}{2}} \left(\frac{u_i}{u_o}\right)^b e^{a(u_o - u_i)} \quad (10)$$

where

$$S = 1 + \frac{2b}{a u_i} + \frac{3b(b-1)}{(a u_i)^2} + \dots \quad (11)$$

Combining this with Eq. (5) gives the breakdown condition. It is an implicit equation for the breakdown field E, occurring on both sides, and has to be solved by trial and error.

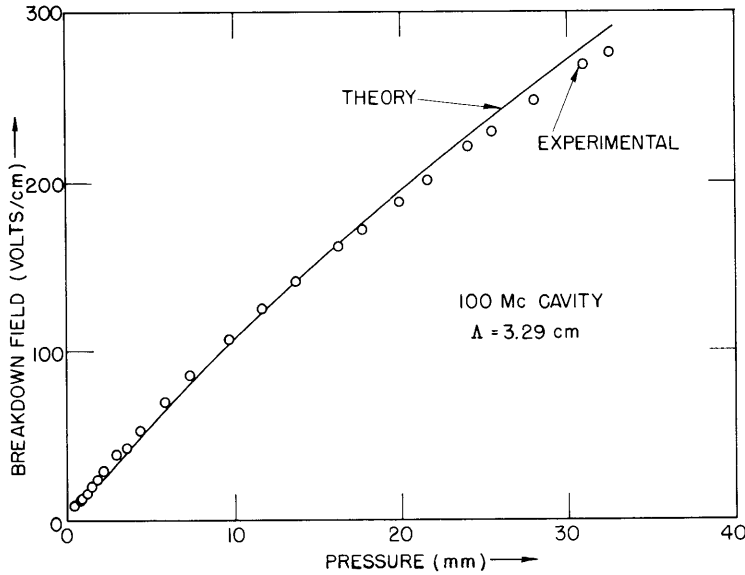


Fig. II-1

Comparison of experiment and theory for the breakdown of hydrogen at 100 Mc.

The quantity u_o comes from joining the two distribution functions (1) and (7), in value and slope, at u_x , and is the energy at which the body function (1) crosses the axis if extended beyond u_x . It is given by the "overshoot"

$$u_o - u_x = \frac{u_x}{\sqrt{b + 1/16}} \quad (12)$$

Calculations of the breakdown fields have been carried out for the 100-Mc cavity. The theoretical results are compared with experimental values in Fig. II-1.

References

- (1) S. C. Brown, A. D. MacDonald: Phys. Rev. 76, 1629 (1949).
- (2) A. D. MacDonald, S. C. Brown: Phys. Rev. 76, 1634 (1949).

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B. POSITIVE ION ANALYSIS

A preliminary check has been made of the operation of all of the components of the mass spectrometer except the magnetic analyzer. It was found that the pumping system was fast enough to allow the cavity to be operated at several mms of Hg of He. The Allen-type electron multiplier appeared to work satisfactorily although the absolute counting rates were too high to be measured with the available scaling circuit. When the discharge was pulsed, the ion current was observed to drop very rapidly when the magnetron was turned off and then to decay to near zero in about 800 μ sec. It was necessary to replace the r-f type high voltage supply for the electron multiplier with a set of 300-volt batteries. A capillary leak was designed which allowed the cavity pressure to be maintained at any desired value in the millimeter range for about one-half hour. This could be used with a liquid helium trap to obtain pure helium for the cavity.

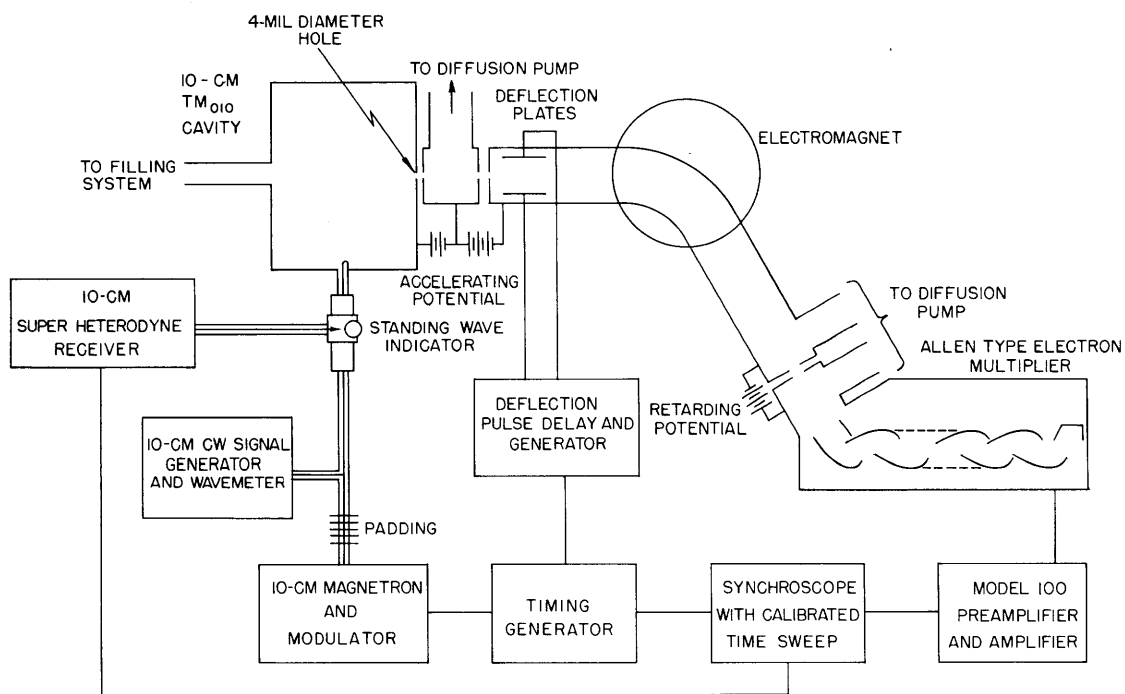


Fig. II-2 Schematic diagram of the apparatus for the analysis of positive ions.

These tests showed the need for several changes which soon will be completed. A set of deflecting plates is being added to the analyzer tube so that the ion beam may be prevented from entering the multiplier except during the measuring interval. Also the slit system has been redesigned in an attempt to approximate more closely the uniform field conditions used at the source in most mass spectrometers to obtain a collimated ion beam. Slits have been added at the collector so that the retarding potential method can be used to reject ions which have lost energy by collisions while traversing the analyzer tube. A schematic diagram of the apparatus for this study is given in Fig. II-2.