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IN AIR OF LOW PRESSURE IN A
COAXIAL PLASMA GUN

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MAGNETIC IGNITION OF PULSED GAS DISCHARGES IN AIR OF LOW PRESSURE IN A COAXIAL PLASMA GUN

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SUMMARY

The effect of an axial magnetic field on the breakdown voltage of a coaxial system of electrodes has been investigated by earlier workers. For low values of gas pressure times electrode spacing, the breakdown voltage is decreased by the application of the magnetic field. The electron cyclotron radius now assumes the role held by the mean free path in nonmagnetic discharges and the breakdown voltage becomes a function of the magnetic flux density. In this paper the dependence of the formative time lag as a function of the magnetic flux density is established and the feasibility of using a magnetic field for igniting high-voltage, high-current discharges is shown through theory and experiment. With a 36 microfarad capacitor bank charged to 48,000 volts, a peak current of 1.3×10^6 amperes in a coaxial type of plasma gun was achieved with a current rise time of only 2 microseconds.

INTRODUCTION

Early investigations have noted that the application of a transverse magnetic field to a system of electrodes carrying an electrical potential can act in such a way as to decrease the breakdown voltage under certain conditions of low pressure and close electrode spacing. (See ref. 1.)

This paper reviews the theoretical work which has been done on this effect and derives a relation for the time required for the discharge to build up. It is reasoned that, since most pulsed electromagnetic plasma guns work under conditions of low gas pressure p and involve small enough electrode spacings d so as to provide a negative slope of the Paschen curve, that is, a pd parameter smaller than the pd corresponding to a minimum breakdown voltage, the effect might well be used as a self-switching plasma gun. Such a gun operating without an external switch, as, for instance, a spark gap, would have a rather low inductance circuit and consequently would have a short current rise time. This short rise time can be achieved, however, only if the discharge buildup time is small compared with the natural time constant of the circuit. Theory shows this to be the case.

A self-switching coaxial plasma gun has been built and the theory has been verified experimentally with good agreement. A maximum current of 1.3×10^6 amperes was achieved.

SYMBOLS

B	magnetic flux density, webers/m^2
D	diameter of cycloid generating circle, m
d	electrode spacing, m
e	electronic charge, coulombs
E	electric field strength, volts/m
I	current, amp
M	multiplication factor, defined by equation (11)
m	mass, kg
n	electron density, 1/m^3
p	pressure, mm Hg
t	time, sec
V_i	ionization potential, volts
v	velocity, m/sec
x	length in direction of electric field, m
$\bar{x}$	mean distance between collision, m
α	First Townsend ionization coefficient, number of ion pairs per m
γ	Second Townsend ionization coefficient

λ	mean free path, m
ν	collision frequency, 1/sec
τ	time constant, sec

Subscripts:

a	azimuthal
c	collision, cyclotron
e	electron
i	ion
max	maximum
o	initial
r	radial
t	at time t

Arrows over symbols indicate vectors.

THEORY

The Breakdown Characteristics

In this section, the conditions for magnetic ignition of an electrical discharge will be explained in a general way. In the section following the principles derived herein will be applied to the experimental setup.

In crossed electric and magnetic fields, the electrons follow cycloidal paths in a direction perpendicular to both the electric and magnetic fields. The assumption is made that the electrodes are much closer together than the ion cyclotron radius. The ions are then practically unaffected by the magnetic field.

If the mean free path is larger than the electron cyclotron radius, the electrons will perform a cycloidal motion in the $\vec{E} \times \vec{B}$ direction between collisions. When a collision occurs, the electron loses a part of its energy. It then starts a new cycloidal motion on a new level which is closer to the anode by approximately the distance of the cyclotron radius. Thus, in the direction of the electric field the cyclotron radius is roughly the distance between collisions instead of the mean free path as is the case where no magnetic field is applied.

The magnetic field in this way acts so as to generate an "equivalent pressure." The ignition of an electrical breakdown by a magnetic field has been explained through the concept of the equivalent pressure by various authors. (See ref. 2.)

Haefer (ref. 1), however, showed that the equivalent-pressure con- L
cept had to be refined. Evaluating his own experimental work and the 1
work of Wehrli and Penning he showed that the minimum breakdown voltage 3
with a transverse magnetic field was not the same as the minimum 3
breakdown voltage indicated on the Paschen curve. 7

Haefer (ref. 1) pointed out that the velocity distribution of the electrons when no magnetic field is applied basically differs from the velocity distribution with a magnetic field. In the first case, the distribution of distances between collisions allows a fraction of the electrons to achieve velocities equivalent to the drop of the electrons through the whole electric field. By investigating electron runaway phenomena, recent workers have shown interest in this fact. (See appendix IV of ref. 3.) In the second case, however, the distance between collisions in the direction of the electric field is limited by the height of the cycloidal arcs. This condition results in a cutoff of the velocity distribution in the case of a transverse magnetic field.

Townsend's first ionization coefficient α measures the number of ion pairs generated per electron and per unit length during the electron's journey from the cathode to the anode. The magnitude of α is

$$\alpha = \frac{1}{\bar{x}} \frac{n(x)}{n_o} \tag{1}$$

where $n(x)$ is the density of electrons with energy greater than or equal to eEx; n_o is the total electron density; and $\bar{x}$ is the mean distance between collisions in the direction of the electric field. The reciprocal of $\bar{x}$ consequently gives the number of collisions per unit length. If x is the distance in the direction of the electric field with $xE = V_i$ and V_i is the ionization potential of the gas molecules, then $n(x)/n_o$ gives the fraction of electrons energetic enough for ionization. Evidently both $\bar{x}$ and $n(x)/n_o$ must have different values in crossed electric and magnetic fields as compared with those obtained in a pure electric field.

Haefer has computed both $\bar{x}$ and $n(x)/n_o$ for crossed electric and magnetic fields. Because of his careful treatment of the different physical situations with the transverse magnetic field applied and because of the good agreement of his findings with experiment, his results are used.

The breakdown criterion, following Townsend's conception of the mechanism of the avalanche process, is (ref. 4, p. 80)

$$\gamma\left(e^{\alpha d} - 1\right) \geqq 1 \tag{2}$$

(see appendix A) where d is the distance between the electrodes and γ is the second ionization coefficient. The following assumptions are made:

(a) that the electric and magnetic fields are homogeneous,

(b) that all collisions with sufficient energy result in ionization,

(c) that after collision the electron starts again with zero initial velocity, and

(d) that the ionization cross section does not vary with velocity.

The magnitudes of $\bar{x}$ and $n(x)/n_o$ for crossed electric and magnetic fields can be derived as in (ref. 1)

$$\bar{x} = \lambda\left(\coth\frac{2D}{\lambda} - \frac{\lambda}{2D}\right) \tag{3}$$

$$\frac{n(x)}{n_o} = \frac{\sinh\frac{2D}{\lambda}\sqrt{1 - \frac{V_i}{ED}}}{\sinh\frac{2D}{\lambda}} \tag{4}$$

where

$$D = \frac{2m_e E}{eB^2} \tag{5}$$

is the diameter of the circle which generates the cycloid, that is, the height of the cycloidal arc and λ is the mean free path.

With equations (2) to (4), the breakdown criterion is

$$\alpha d = \log_e\left(1 + \frac{1}{\gamma}\right) = \frac{d \sinh \frac{2D}{\lambda} \sqrt{1 - \frac{V_i}{ED}}}{\lambda\left(\coth \frac{2D}{\lambda} - \frac{\lambda}{2D}\right)\sinh \frac{2D}{\lambda}} \tag{6}$$

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for the case of homogeneous crossed electric and magnetic fields and the spacing of the electrodes equal to d.

Equation (6) gives a relation between E and B for which breakdown occurs, depending upon γ, d, V_i, and λ. These magnitudes generally are determined by the particular experimental setup.

In general, equation (6) is difficult to solve for E and B. However, for certain values of λ, E, and B, equation (6) can be simplified. In the following section such a simplification is shown to be applicable to the case of the magnetic ignition described in the paper.

Breakdown Conditions for Specific Experimental Setup

The experimental setup of the magnetically ignited switch was determined by the requirements of an electromagnetic plasma accelerator. The inner diameter of the outer electrode was chosen to be 0.06 meter. The filling gas was air under a pressure of 10^{-2} millimeters of mercury. The diameter of the inner electrode was determined from the usual Paschen curves under the condition that no breakdown should occur when an electric potential of 25,000 volts was applied.

Experimental data for high-voltage breakdown potentials with steel electrodes in air were furnished by Quinn. (See ref. 4, p. 96.) According to his data, a gap of 0.01 meter should stand off a potential considerably greater than 25,000 volts at a pressure of 10^{-2} mm Hg.

The diameter of the inner electrode was therefore chosen as 0.04 meter and allows a clearance of 0.01 meter between the electrodes. (See fig. 1.) The product of pressure and electrode gap pd is thus fixed by the experimental setup: $pd = \left(10^{-2}\text{ mm Hg}\right)\left(0.01\text{ meter}\right)$.

By early investigations on the magnetic ignition of an electrical discharge in air, Wehrli (ref. 1) established the fact that, for certain values of $pd = (pd)_{critical}$, no influence of the transverse magnetic field on the breakdown could be observed. For pd values greater than $(pd)_{critical}$, the breakdown voltage was increased by the application of the magnetic field whereas, for pd less than $(pd)_{critical}$, it was decreased. Wehrli's conclusions have been confirmed by other workers, both experimentally and theoretically.

This critical value $(pd)_{critical}$ has been found and confirmed as

$$(pd)_{critical} \approx \left(10^{-2} \text{ mm Hg}\right)(m)$$

(See ref. 1.) Consequently, in the pressure range under consideration and with the particular arrangement of the electrodes, the application of a transverse magnetic field must be expected to decrease the breakdown voltage and to ignite the electrical discharge. With d, λ, V_i, E, and γ (see appendix A) fixed, equation (6) can be used to determine the breakdown voltage as a function of the magnetic flux density.

If the breakdown condition is approached from high values of B, $2D/\lambda$ being much less than 1, equations (3) and (4) can be simplified by expanding the coth term in a series and taking only the first two terms. Also the approximation $\sinh x \approx x$ can be used to obtain the result

$$\bar{x} = \lambda\left(\coth \frac{2D}{\lambda} - \frac{\lambda}{2D}\right) \approx \frac{2}{3}D \tag{7}$$

$$\frac{n(x)}{n_o} = \frac{\sinh \frac{2D}{\lambda}\sqrt{1 - \frac{V_i}{ED}}}{\sinh \frac{2D}{\lambda}} \approx \sqrt{1 - \frac{V_i}{ED}} \tag{8}$$

for $\frac{2D}{\lambda} \ll 1$. (See appendix B.)

Equation (6) then becomes

$$\alpha d = \log_e\left(1 + \frac{1}{\gamma}\right) = \frac{3}{2}\frac{d}{D}\sqrt{1 - \frac{V_i}{ED}} \tag{9}$$

Equation (9) yields the critical breakdown voltage as a function of the magnetic flux density. With $\gamma = 0.01$, $d = 0.01$ meter, and $V_i = 15.5$ volts, equation (9) becomes for the case of the switch. (See appendix C.)

$$E = \left(2.08 \times 10^8\right) B^2 \sqrt{1 \pm \sqrt{1 - \frac{6.6 \times 10^{-5}}{B^2}}} \tag{10}$$

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The dependence of the breakdown voltage on the magnetic flux density at 10^{-2} mm Hg pressure in air and with an electrode spacing of 0.01 meter is plotted in figure 2. The lower branch of the curve in figure 2 corresponds to the minimum electron energy for ionization. The upper branch corresponds to the requirement of sufficient electron amplification for causing breakdown. The reader may be somewhat disturbed to see that there is a limiting electric field above which a breakdown cannot take place. However, since the effective distance between collisions in the direction of the electric field varies as D which, in turn, varies as E, then $\bar{x} \propto E$. Thus, as the electric field increases, the distance between collisions may become so large that there is insufficient electron multiplication for a self-sustaining avalanche to form. From equation (9) the area between the two branches in figure 2 is the area where the breakdown conditions are fulfilled.

It should be mentioned that in relations (7) and (8), under the condition $2D/\lambda \ll 1$, the gas pressure canceled out of the breakdown conditions. This result could have been expected from the physical picture. At low pressure and for strong magnetic fields, the height of the cycloidal arcs becomes the important length of interest in the direction of the electric field instead of the mean free path λ.

The Formative Time Lag

The formative time lag is the time required for a discharge current to build up from an initial current to its final value. For a magnetically initiated discharge to be useful for obtaining high-powered pulses, this time lag must be small compared with the natural current rise time of the circuit.

The description of the increase of current with time during the breakdown process is carried out in a similar analysis to that made by Penning (ref. 4, p. 114) of the formative time lag in the usual breakdown process where no magnetic field is applied. The applicability of this analysis to the experimental conditions described is discussed in appendix D.

In Penning's treatment, attention is given to the Townsend breakdown mechanism where the magnitude αd determines the growth of the avalanche of ion pairs and where the factor γ determines the increase of the number of avalanches. The amplification of the current then depends on both αd and γ. The time dependency of the increase of the current consequently depends on the intensity of the avalanches and their repetition with time.

The multiplication of electrons due to one cycle of starting electrons is

$$M = \gamma\left(e^{\alpha d} - 1\right) \tag{11}$$

The repetition rate for the cycles ordinarily is the transit time of the ions traveling from the anode to the cathode. The increase of current with time is then described by the number of repetitions of the multiplication M in the form of a geometric sum of M.

$$I_t = I_o \frac{M^{k+1} - 1}{M - 1} \tag{12}$$

Since k is the number of repetitions of avalanches and τ_i is the ion transit time in seconds, then $t = k\tau_i$. With $k \gg 1$ and $M > 1$, equation (12) becomes

$$k \log_e M = \log_e\left[\frac{I_t}{I_o}(M - 1)\right] \tag{13}$$

and the time for the increase of the current is

$$t = \tau_i \frac{\log_e\left[\frac{I_t}{I_o}(M - 1)\right]}{\log_e M} \tag{14}$$

where I_o is the initial current and I_t is the current at time t.

Equation (14) treats the ion transit time τ_i as a fundamental magnitude because of the fact that, when no transverse magnetic field is applied, the avalanche repetition rate is determined by the slow ions. When a transverse magnetic field is applied, the electrons do not necessarily travel the distance between the electrodes faster than the ions do.

The average velocity for electrons in the azimuthal direction is $v_a = \frac{E}{B}$. The time between collisions then is $t_c = \frac{\lambda}{E/B}$. The collision frequency is $\frac{1}{t_c} = \frac{E/B}{\lambda} = \nu_c$. The distance gained in the direction of the electric field at each collision is $\frac{2}{3}D$. The radial velocity of the electrons then is

$$v_r = \nu_c \frac{2}{3}D = \frac{4}{3}\left(\frac{E}{B}\right)^2 \frac{1}{\lambda} \frac{1}{B} \frac{m_e}{e} \tag{15}$$

for homogeneous electric and magnetic fields and for $2D/\lambda \ll 1$. The radial velocity of the electrons thus decreases with increasing magnetic flux density. For the conditions of the plasma gun this dependency is plotted in figure 3.

The ratio of the azimuthal velocity to the radial velocity then is

$$\frac{v_a}{v_r} = \frac{3}{4} \frac{B^2}{E} \lambda \frac{e}{m_e} \tag{16}$$

Because of their greater mass, the ions are practically not affected by the magnetic field as their radius of gyration is much larger than the electrode spacing. They consequently cannot follow an $\vec{E} \times \vec{B}$ drift motion around the inner electrode. If it is assumed that, under low pressure the electrons will not drag the ions along with their motion, at least not for a transient period of time, equations (15) and (16) can be interpreted as the creation of a strong Hall current in the circumferential direction. For the conditions of the switch, equation (16) has been computed and the dependency of v_a/v_r on B is shown in figure 4. With a transverse field of 0.2 weber/m^2, this Hall current is about 10 times larger than the radial current.

At a pressure of 10^{-2} mm Hg, the mean free path at room temperature is of the order of the electrode spacing. The ion velocity may then be computed from the drop through the whole potential. From $v_i = \sqrt{\frac{2e}{m_i} V}$ follows

$$v_i \approx 4.12 \times 10^5 \ \frac{m}{sec} \tag{17}$$

where $m_i = 4.68 \times 10^{-26}$ kilograms.

The comparison with figure 3 shows that, for the case of the magnetically ignited plasma gun, the electron and ion velocities are equal when the magnetic flux density is about 0.3 weber/m^2. For higher values of B, the electron velocity drops appreciably under the ion velocity. The repetition rate of avalanches is thus also determined by the electron transit time τ_e. Equation (14) then becomes

$$t = \left(\tau_i + \tau_e\right)\frac{\log_e\left[\frac{I_t}{I_o}(M - 1)\right]}{\log_e M} \tag{18}$$

Since τ_e and M are functions of B, the time t becomes a function of the magnetic flux density too.

The variation of the multiplication factor α with magnetic flux density according to equation (9) is represented in figure 5 for the case of the plasma gun.

From the values of α in figure 5, one notes that, for $0.3 < B < 1$, αd is of the order of 50 to 500. Consequently, $e^{\alpha d} \gg 1$ and M simplifies from equation (11) to

$$M = \gamma e^{\alpha d} \tag{19}$$

For these magnitudes $\gamma e^{\alpha d} \gg 1$ and equation (18) can be approximated as

$$t = \left(\tau_e + \tau_i\right)\frac{\log_e M\frac{I_t}{I_o}}{\log_e M} \tag{20}$$

for $B > 0.3$ weber/m^2. The magnitude I_t/I_o may be determined from one electron starting the breakdown process and setting $I_t = 10^6$ amperes. For an electron transit time of 2.5×10^{-8} seconds the ratio I_t/I_o is of the order of 10^{17} and $\log_e \frac{I_t}{I_o} \approx 39$. The formative time lag, equation (20), is then approximately

$$t = \left(\frac{d}{v_i} + \frac{d}{v_e}\right)\left(1 + \frac{39}{\alpha d - 4.6}\right) \tag{21}$$

For a magnetic flux density of about 0.3 weber/m^2, the time lag is computed as $t \approx 10^{-7}$ seconds. For smaller values of the igniting magnetic field, the formative time lag has to be determined as

$$t = \left(\frac{d}{v_{er}} + \frac{d}{v_{ir}}\right)\left\{\frac{\log_e\left[\gamma\left(e^{\alpha d} - 1\right) - 1\right] + \log_e \frac{I_t}{I_o}}{\log_e \gamma + \log_e\left(e^{\alpha d} - 1\right)}\right\} \qquad (22)$$

The formative time lag according to equation (22) and for the plasma gun under description is plotted in figure 6.

For B values smaller than 0.094 weber/m^2, the time lag in figure 6 approaches infinity in agreement with the breakdown condition of figure 2, where a magnetic field of about 0.094 weber/m^2 is indicated to ignite the discharge of a potential of 25,000 volts.

According to figure 6, the formative time lag decreases rapidly when the magnetic flux density slightly exceeds the breakdown minimum. In order to achieve a fast rise of current, a delay of the ignition with regard to the rise of the magnetic field should be created. This delay is furnished by the statistical time lag. (See ref. 4, p. 111.)

According to figure 6, the discharge should happen within a fraction of a microsecond, a time interval appreciably shorter than those determined by the electrical circuit characteristics. Thus a rapid ignition of the gas discharge by means of the magnetic field appears to be feasible.

EXPERIMENTAL WORK

Apparatus

An overall view of the apparatus is shown in figure 7. The gun is designed to keep inductance low. From each of the 36 1-microfarad, 50,000-volt low-inductance capacitors an RG 8/U coaxial cable carries the power to the gun. The coaxial sheaths are grounded to the brass outer cylinder of the switch. The inner conductors of the coaxial lines are led to the center electrode. A Lucite cylinder between the outer brass cylinder and the inner leads insulates the two electrodes from each other. A stainless-steel cylinder, 0.06 meter inside diameter, and a stainless-steel rod with a rounded end comprise the coaxial electrodes. Assembly views are shown in figure 8.

A pressure of less than 10^{-2} millimeters of mercury is maintained in the chamber. The magnetic field for triggering is provided by a 1,500-turn coil fitting over the outer electrode. This coil is powered by a bank of storage batteries. The battery-coil circuit also includes a shunted ammeter and a remote-controlled rheostat. The discharge characteristics are measured by an oscilloscope. An electrostatic voltmeter measures the voltage across the capacitor bank.

Experimental Results

Figure 2 shows the region where, according to equation (6), the breakdown can occur. In order to verify this equation experimentally, two methods were employed in order to approach the breakdown area from both its lower and upper limit.

In order to get the lower limit of the breakdown region the magnetic flux density was held at a constant value by setting the current in the coil and then the voltage was raised until breakdown occurred. The values of the electric field strengths for breakdown thus obtained are plotted as circles in figure 9. The upper limit is approached by setting the voltage and raising the magnetic flux density until breakdown occurs. These values are shown as triangles in figure 9. From this figure it is seen that most of the circles fall on the lower branch of the curve with good agreement; however, most of the triangles fall well within the breakdown region. This condition may possibly be explained by the fact that the upper curve was approached by holding the voltage constant and switching on the magnetic field instead of raising it with the rheostat. The rise time for the current in the coil was on the order of 50 milliseconds which may well have compared with the statistical time lag. Thus the magnetic field would have risen to a higher value before the breakdown occurred and the higher value resulted in the observed shift to the right of the experimental points near the upper branch of the curve in figure 9.

In order to verify the feasibility of a fast discharge the capacitor bank was charged to 48,000 volts and the discharge was ignited magnetically. The time τ for a full cycle of the oscillatory discharge was measured from oscillographs. This value was 8 microseconds. The current rise time was 2 microseconds. The fact that a pure sinusoidal variation of the discharge current was obtained with a 2 microsecond rise time indicates that the formative time lag must have been less than a microsecond as theory predicts. By neglecting ohmic damping, the maximum current was

$$I_{max} = \frac{2\pi CV}{\tau}$$

where C was the capacitance of the capacitor bank $(3.6 \times 10^{-5}$ farad) and V was the voltage $(4.8 \times 10^{4}$ volts). Thus the maximum current was 1.3×10^{6} amperes.

CONCLUDING REMARKS

The magnetic ignition of an electrical discharge in a plasma gun has
the advantage of omitting an extra switching device. In plasma propul- L
sion systems or in devices for nuclear fusion research, the elimination 1
of an extra switch represents first an improvement, because the lower 3
inductance of the circuit results in a shorter rise time of the current 3
and thus higher currents are obtainable. Second, the magnetic ignition 7
causes a breakdown under very low pressure where, according to the Paschen curves, no ordinary breakdown can occur. Finally, the generation of azimuthal Hall currents leads to more effective methods of plasma propulsion or to better ways for transferring electrical energy to plasmas.

The use of the magnetically triggered discharge to achieve very high currents in a short time depends upon the formative time lag being small enough. That the time lag is small has been shown both theoretically and experimentally.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Field, Va., April 17, 1961.

APPENDIX A

TOWNSEND BREAKDOWN CRITERION

The Townsend breakdown criterion

$$\gamma\left(e^{\alpha d} - 1\right) \geqq 1$$

may be developed, term by term, as follows:

$e^{\alpha d}$ measures the number of ions pairs generated per electron over the distance d between the electrodes.

$\left(e^{\alpha d} - 1\right)$ is the number of ions impinging upon the cathode.

$\gamma\left(e^{\alpha d} - 1\right)$ is the number of secondary electrons.

$\gamma\left(e^{\alpha d} - 1\right) \geqq 1$ then means that all ions should at least generate one new electron for starting a new avalanche.

The second Townsend ionization coefficient γ measures all secondary electrons generated in the discharge volume. The main contribution to γ is thought to be the liberation of electrons by ion bombardment of the cathode. This part of γ, of course, depends basically on the work function of the cathode material and on the energy of the ions. It may also depend upon the transverse magnetic field, since at low pressure electrons will return to the cathode if they lose no energy due to collisions on the first cycloidal arc.

The determination of the exact value of γ turns out to be rather difficult. The investigation of the dependency of γ on different gases, different cathode materials, and different ion energy levels has been carried out by a number of workers. (See refs. 4 and 5.)

Generally γ increases with increasing ion energy. Over a wide range of energy in the 100 Kev range, γ remains almost constant. For still higher energies γ drops slowly. In the range of maximum γ values, γ attains a magnitude of 10 according to measurements of Hill and other workers. (See ref. 5, p. 549.)

Measurements by Llewellyn, Jones, and Davies (ref. 5, p. 479) of oxidized nickel electrodes in air give a γ value of 0.01 in the 10 eV range. Haefer (ref. 6) uses γ values of 2×10^{-2} and smaller.

In the theoretical treatment of the magnetic ignition, a γ value of 10^{-2} has been used. It should be emphasized, however, that this choice is somewhat arbitrary.

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APPENDIX B

RELATIONSHIP BETWEEN THE CYCLOTRON DIAMETER AND THE MEAN FREE PATH

The approximations used are the same as those used by Haefer (ref. 1). Haefer points out that the maximum error in equation (7) does not exceed 10 percent for $2D/\lambda$ values up to 1.3.

The condition that $2D/\lambda < 1.3$ demands that the height of the cycloidal arcs shall not be greater than approximately one-third of the distance between the electrodes since the mean free path λ shall be of the order of the electrode spacing.

From the breakdown mechanism involving avalanche processes, one must assume that the actual ratio of $2D/\lambda$ is much smaller than unity when breakdown occurs. Thus $2D/\lambda \ll 1$ is valid for any approach to the breakdown condition, either from high B values or low B values for the particular case of the described discharges.

APPENDIX C

BREAKDOWN EQUATION FOR THE CASE OF THE MAGNETICALLY INITIATED DISCHARGE

The breakdown equation for the case of the magnetically initiated discharge is developed as follows:

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From equation (9)

$$\log_e\left(1 + \frac{1}{0.01}\right) = \log_e 101 = 4.6 = b = \frac{3 \times 10^{-2}}{2a} \frac{B^2}{E} \sqrt{1 - \frac{V_i}{a} \frac{B^2}{E^2}} \tag{C1}$$

From equation (5)

$$D = \frac{2m}{e} \frac{E}{B^2} = a\frac{E}{B^2} \tag{C2}$$

where

$$a = \frac{2 \times 9 \times 10^{-31}}{1.6 \times 10^{-19}} \approx 11.3 \times 10^{-12} \frac{\text{kg}}{\text{coulomb}} \tag{C3}$$

Substituting equations (C2) and (C3) into equation (C1) and simplifying yields

$$\left(\frac{2ab}{3 \times 10^{-2}} \frac{E}{B^2}\right)^2 = \left(\frac{4}{9} \frac{a^2b^2}{B^2} \times 10^4\right)\left(\frac{E}{E}\right)^2 = 1 - \frac{V_i}{a}\left(\frac{B}{E}\right)^2$$

$$\left(\frac{4}{9} \frac{a^2b^2}{B^2} \times 10^4\right)\left(\frac{E}{B}\right)^4 - \left(\frac{E}{B}\right)^2 + \frac{V_i}{a} = 0$$

$$\left(\frac{E}{B}\right)^4 - \left(2\frac{9}{8} \frac{B^2}{a^2b^2} \times 10^{-4}\right)\left(\frac{E}{B}\right)^2 + \left(\frac{9}{4} \frac{V_i}{a^3b^2} \times 10^{-4}\right)B^2 = 0$$

$$\left[\left(\frac{E}{B}\right)^2 - \left(\frac{9}{8}\,\frac{B^2}{a^2b^2} \times 10^{-4}\right)\right]^2 = \left[\left(\frac{9}{8}\right)^2 \frac{B^4}{a^4b^4} \times 10^{-8}\right] - \left(\frac{9}{4}\,\frac{V_iB^2}{a^3b^2} \times 10^{-4}\right)$$

$$\left(\frac{E}{B}\right)^2 = \left(\frac{9}{8}\,\frac{B^2}{a^2b^2} \times 10^{-4}\right) \pm \sqrt{\left[\left(\frac{9}{8}\right)^2 \frac{B^4}{a^4b^4} \times 10^{-8}\right] - \left(\frac{9}{4}\,\frac{V_iB^2}{a^3b^2} \times 10^{-4}\right)}$$

$$E = \left(\frac{3}{\sqrt{8}}\,\frac{B^2}{ab} \times 10^{-2}\right)\sqrt{1 \pm \sqrt{1 - \left(\frac{16}{9}\,\frac{ab^2V_i}{B^2} \times 10^4\right)}}$$

$$E = \left(2.08 \times 10^8\right)B^2\sqrt{1 \pm \sqrt{1 - \left(\frac{6.6}{B^2} \times 10^{-5}\right)}}\ \frac{\text{volt}}{\text{m}} \qquad \text{(C4)}$$

APPENDIX D

SPACE CHARGE EFFECT

In the treatment of the time dependency of the increase of current, no consideration is given to the space charge which develops in the volume between the electrodes due to the different mobilities of electrons and ions in the direction of the electric field. The resulting distortion of the electric field tends to cause strong potential drops close to either cathode or anode depending upon whether electrons or ions drop faster through the electric field when a transverse magnetic field is applied. As a result the E/B magnitude in the volume between the electrodes may change due to the space charge and thus change the breakdown conditions. A more detailed analysis of the breakdown process in time should take into account the space charge effect.

Experience, however, justifies the neglect of space charge processes in transient discharges in that the process described herein never stopped the radial current due to effects which could be related to space charge.

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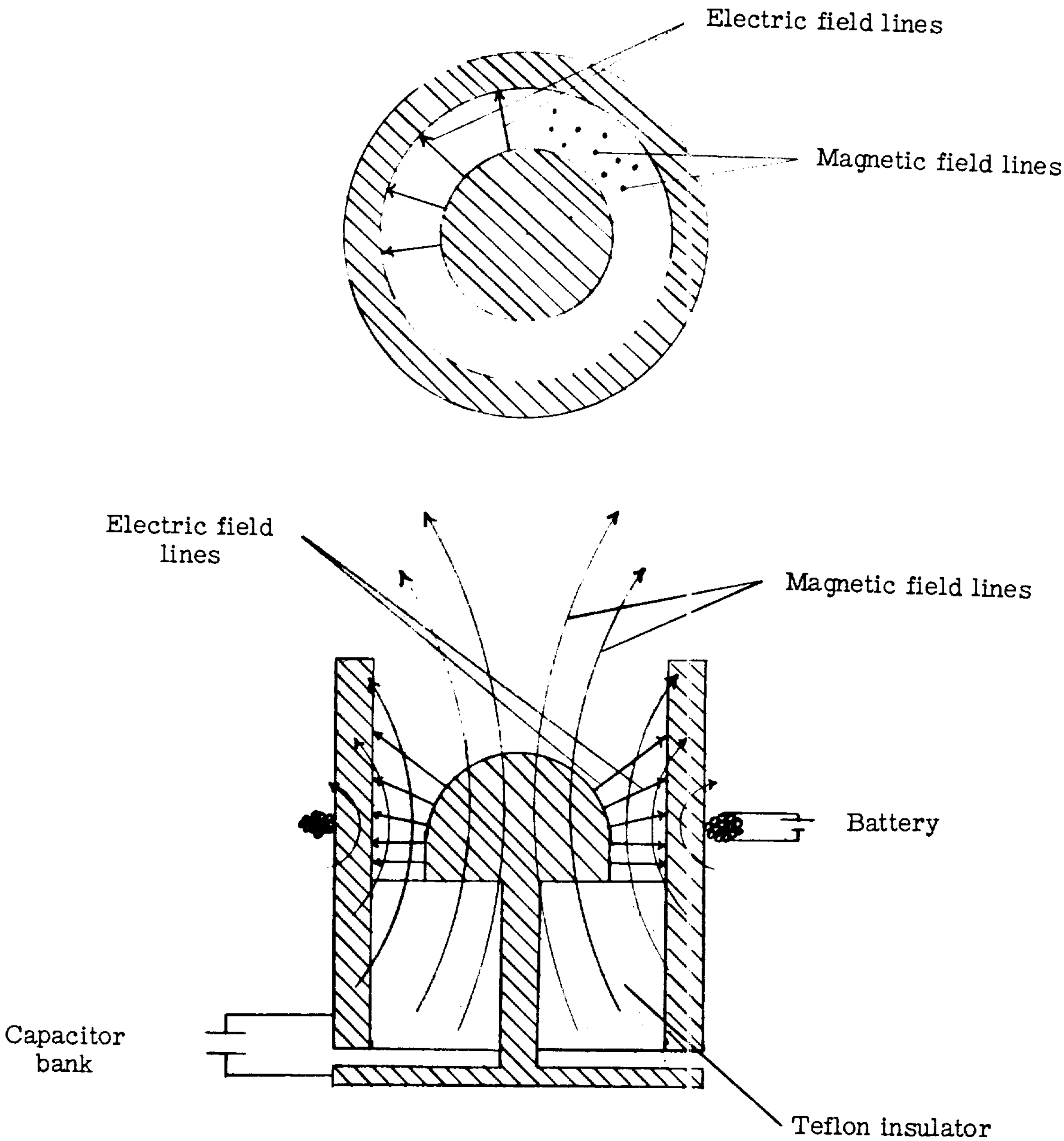

Figure 1.- Schematic view of plasma gun.

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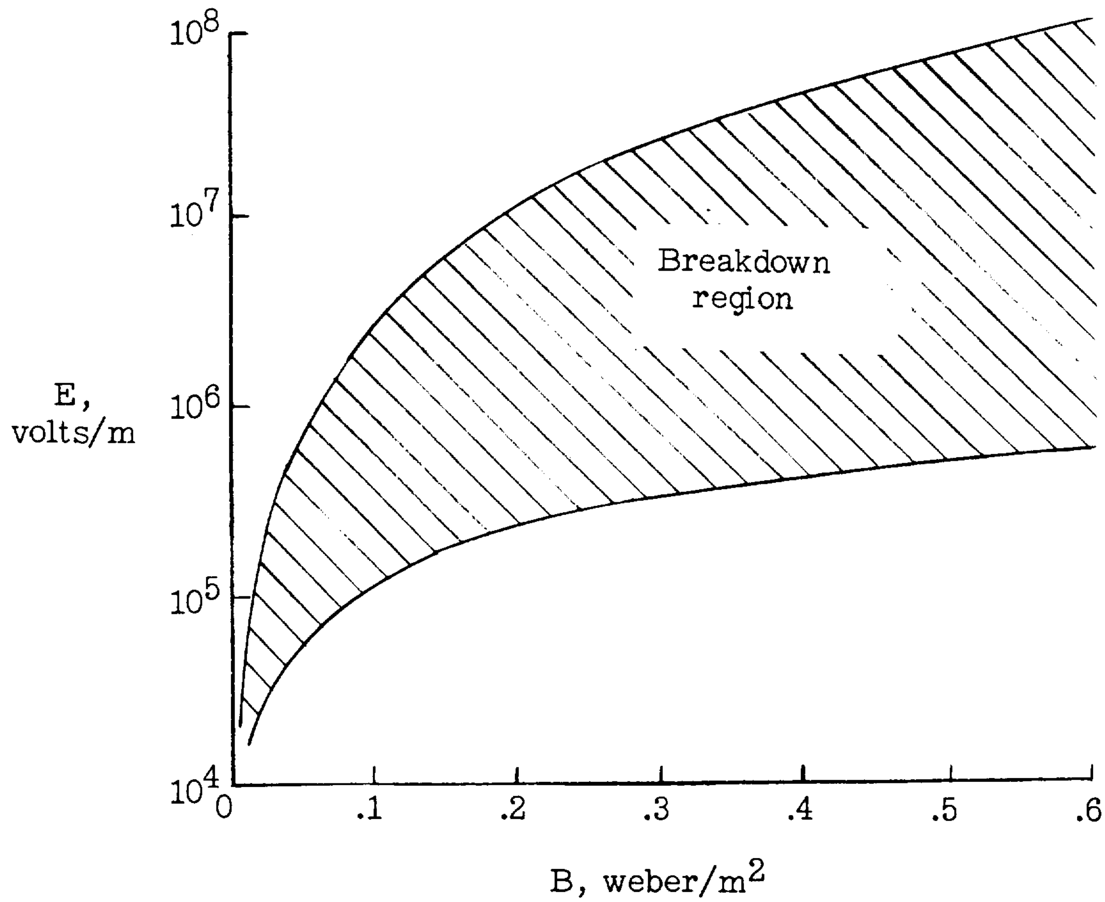

Figure 2.- Electric field strength for breakdown depending on the magnetic flux density. $p = 10^{-2}$ mm Hg; $d = 0.01$ m.

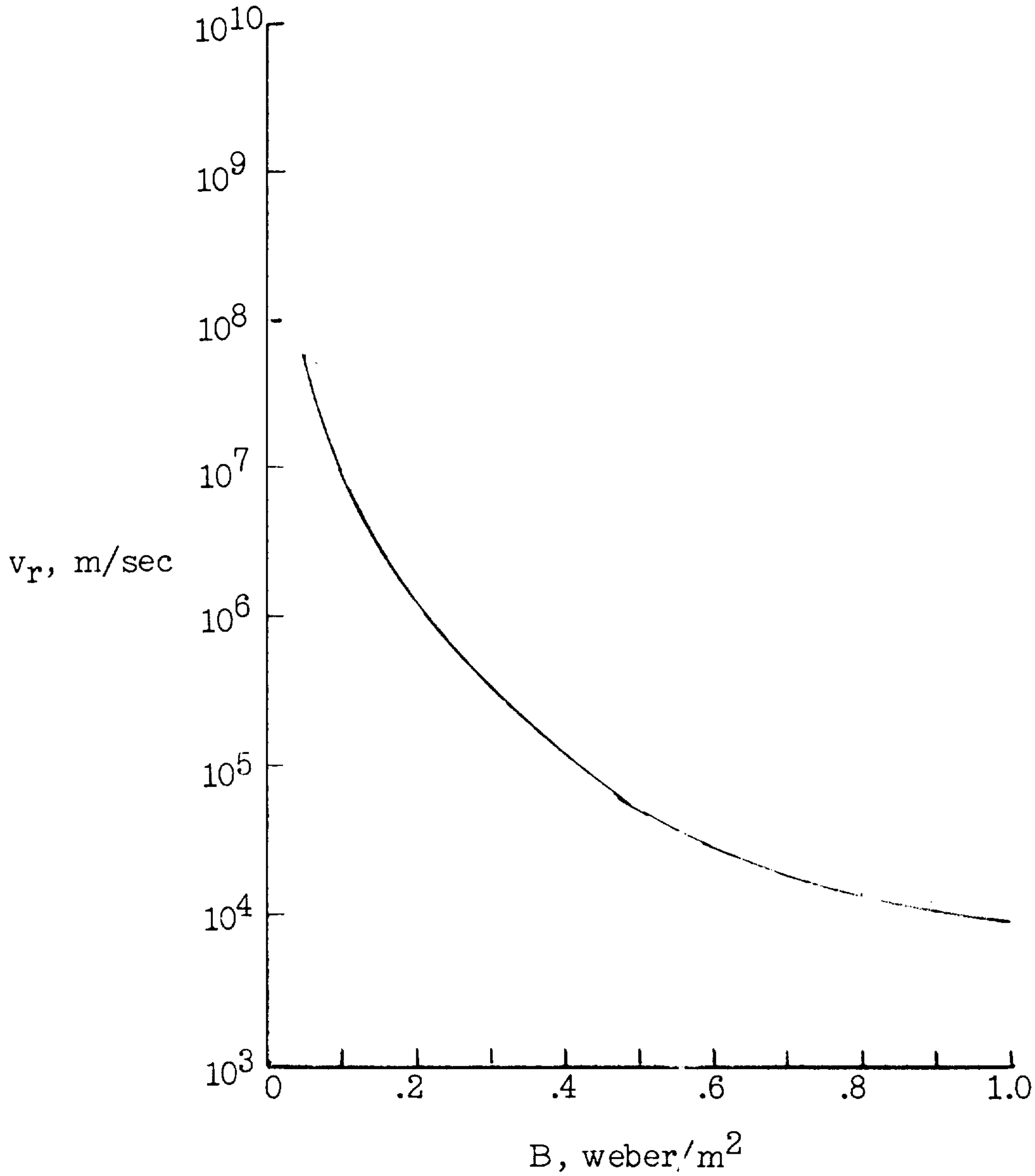

Figure 3.- Radial electron velocity depending upon the magnetic flux density. V = 25,000 volts; p = 10^{-2} mm Hg; d = 0.01 m.

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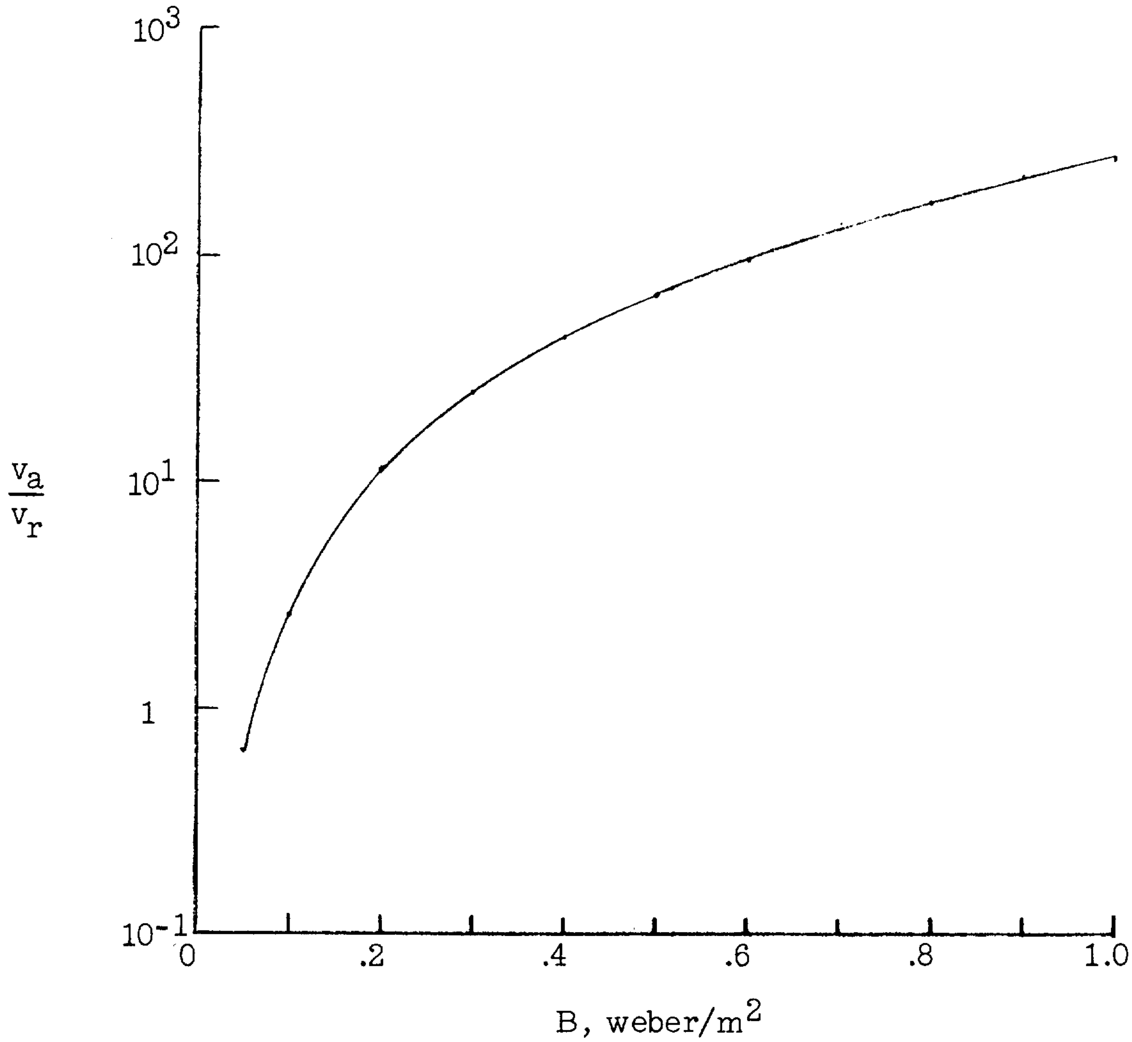

Figure 4.- Ratio of azimuthal to radial electron velocity depending on the magnetic flux density. $V = 25{,}000$ volts; $p = 10^{-2}$ mm Hg; $d = 0.01$ m.

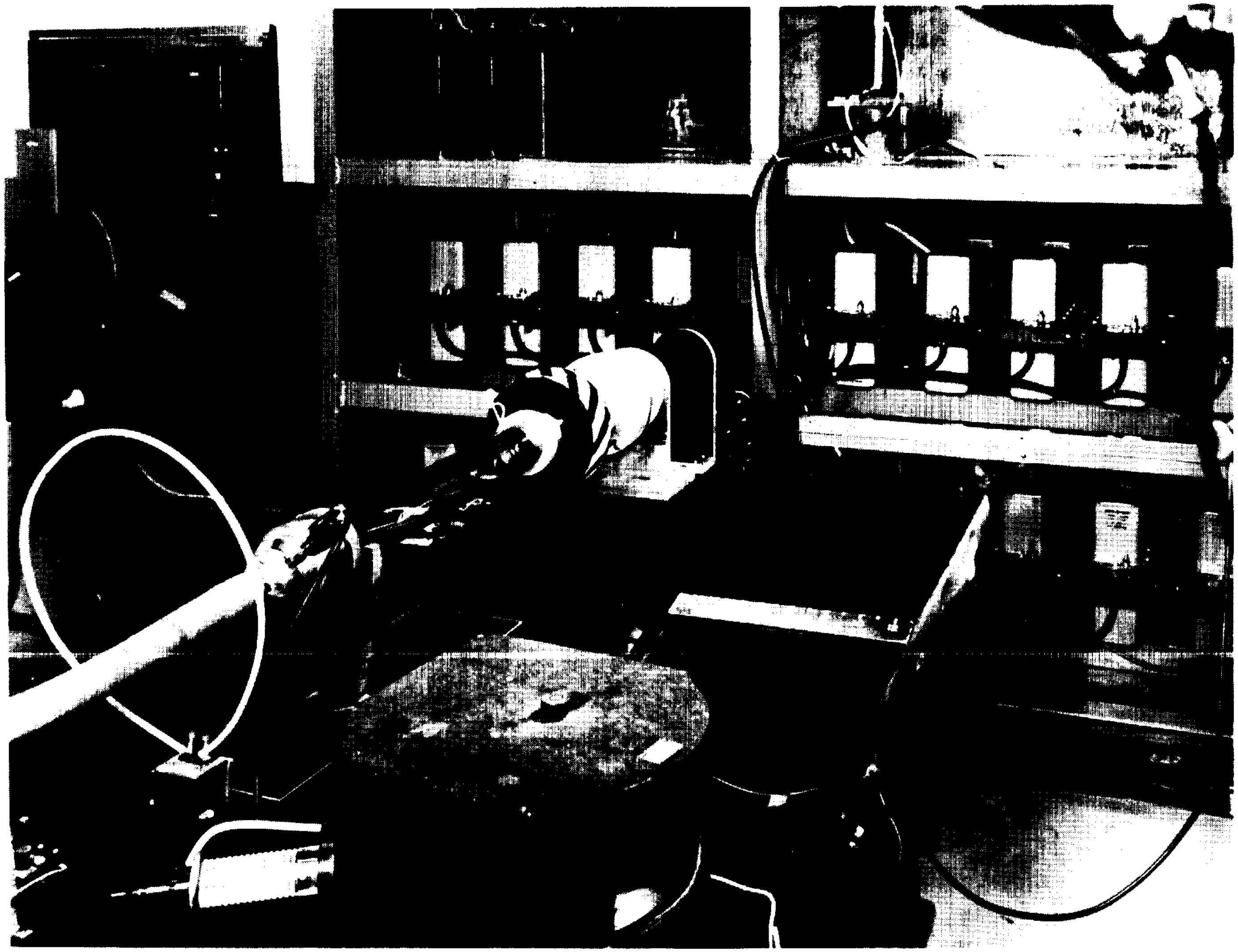

Figure 7.- Overall view of apparatus. L-60-5370

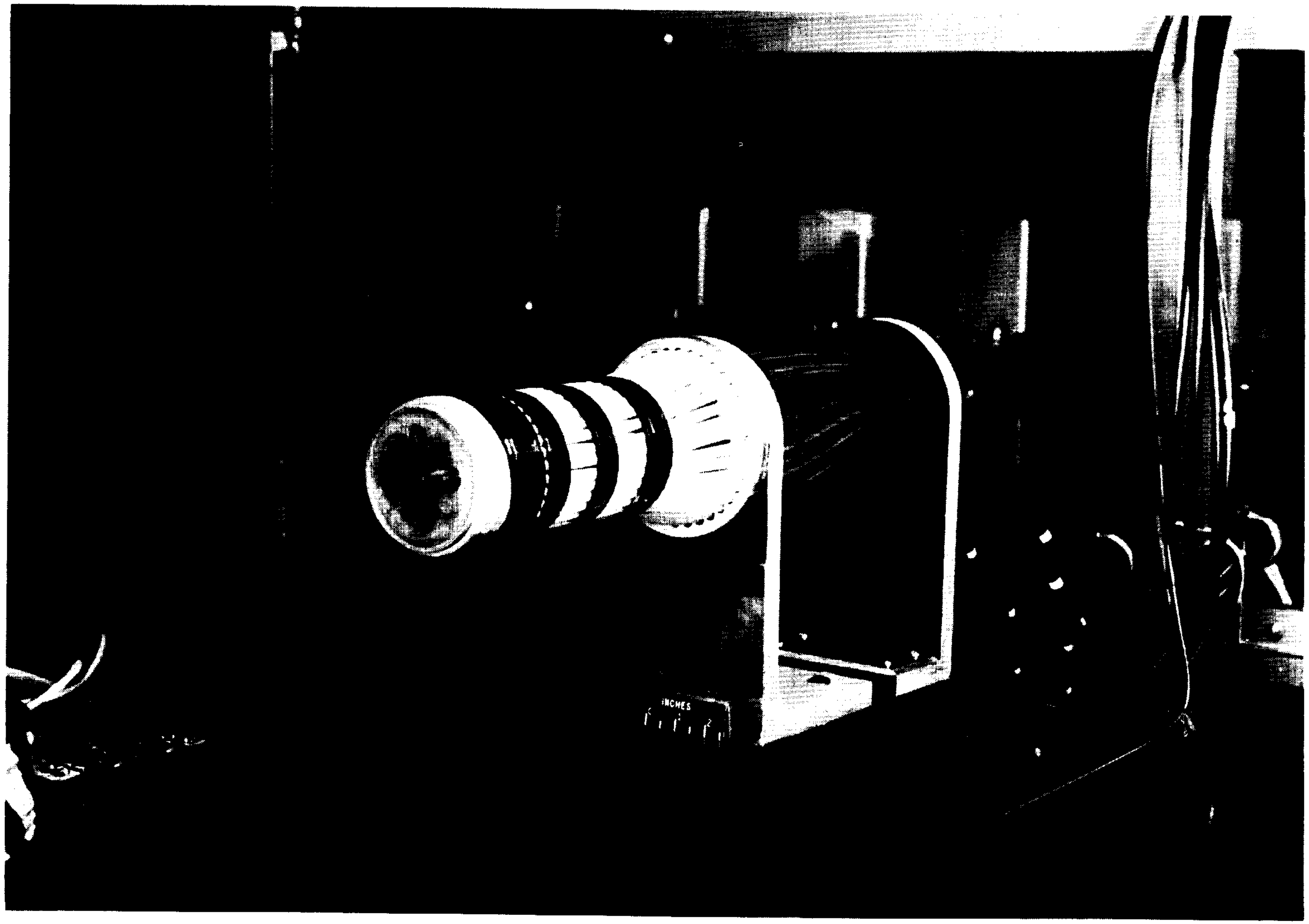

Figure 8.- Assembly view. L-60-5667

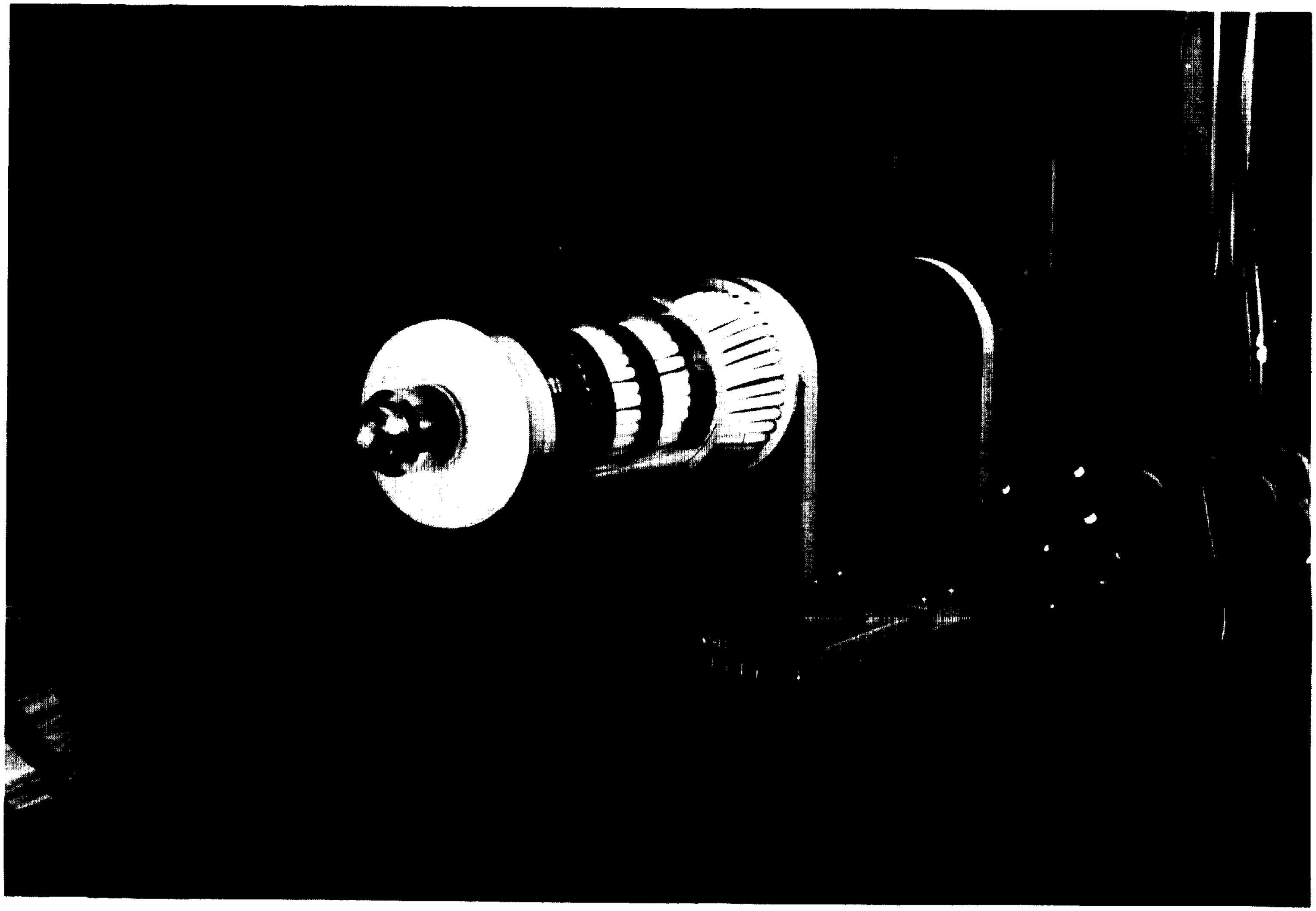

Figure 8.- Continued. L-60-5668

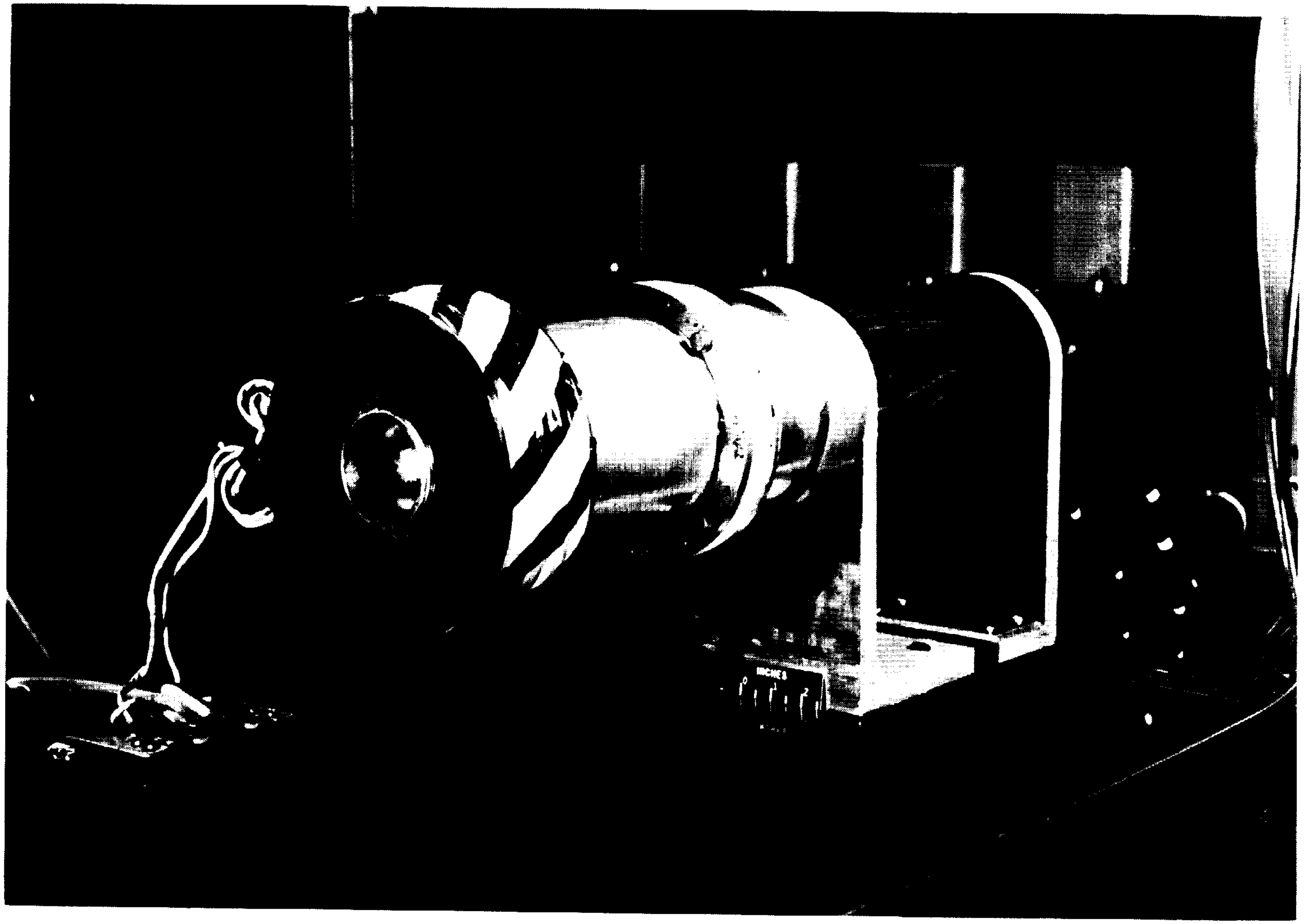

Figure 8.- Concluded. L-60-5669

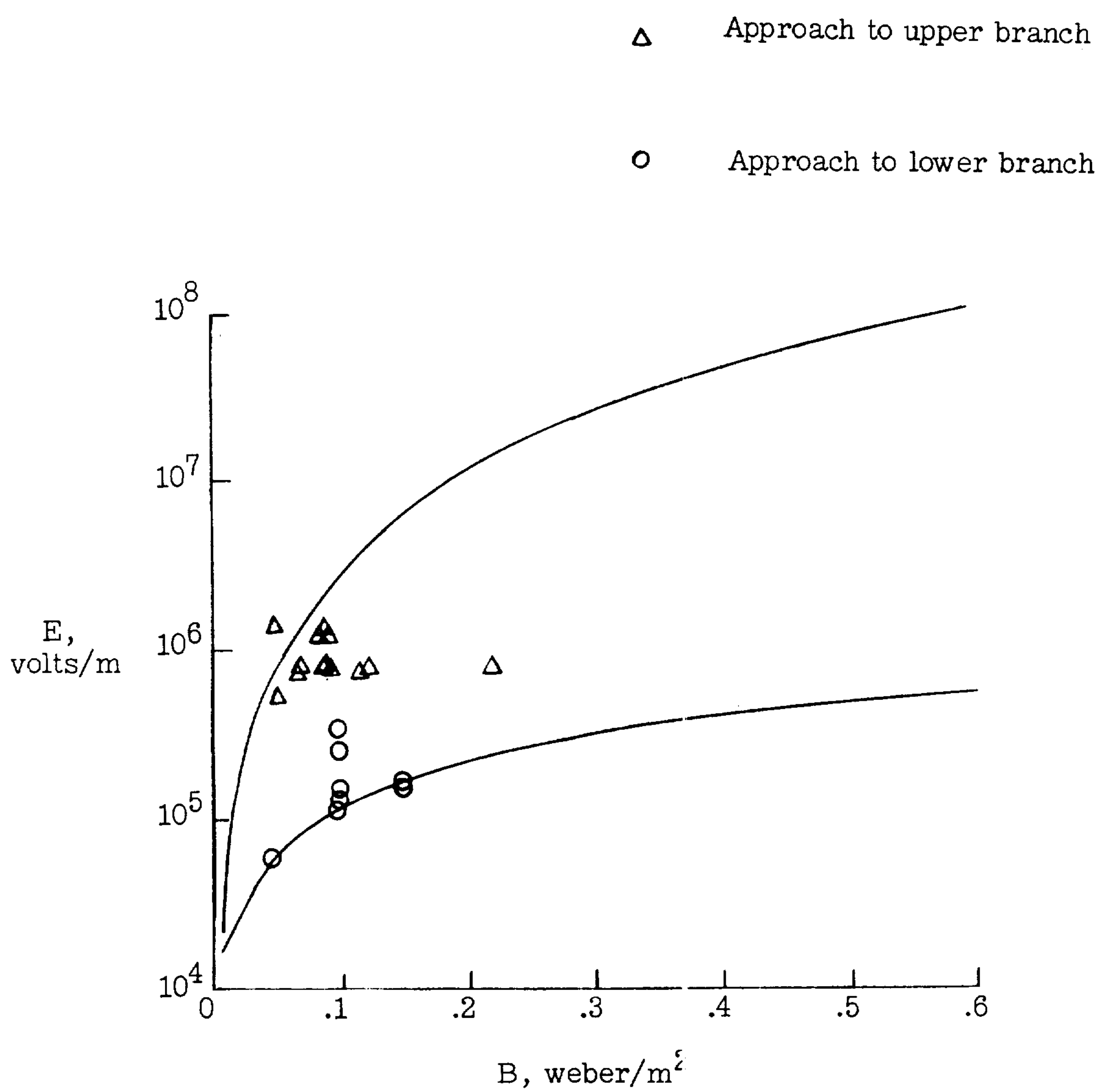

Figure 9.- Experimental evaluation of electric field strength for breakdown depending upon the magnetic flux density. $p = 10^{-2}$ mm Hg; $d = 0.01$ m.

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