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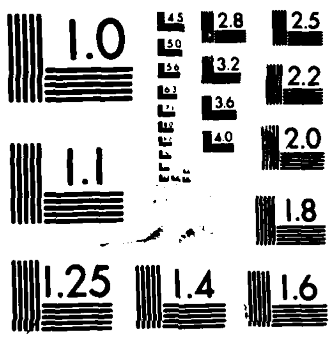

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DEPARTMENT OF ELECTRICAL ENGINEERING
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OLD DOMINION UNIVERSITY
NORFOLK, VIRGINIA 23508

MAGNETIC CONTROL OF LOW-PRESSURE DISCHARGES

By

Karl H. Schoenbach, Principal Investigator

Progress Report
For the period ended August 15, 1986

Prepared for the
Head, Physics Division
Office of Naval Research
800 North Quincy Street
Arlington, VA 22217-5000

Under
Research Contract N00014-85-K-0602
B. R. Junker, Scientific Officer
Code 1112

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In low pressure discharges, operated in electronegative gas mixtures to the right of the Paschen curve minimum, the discharge resistance can be increased by application of transverse magnetic fields. This effect allows the use of a magnetically-controlled glow discharge as an opening switch with submicrosecond opening time, or to shorten the recovery time considerably if it is used as a closing switch.

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The application of a magnetic field transverse to an electric field in a low pressure discharge causes a shift in the electron energy distributions towards lower energies. This shift affects the transport and rate coefficients, and consequently the resistance of the discharge. In order to model magnetically-controlled glow discharges Monte-Carlo codes are used to determine the rate and transport coefficients in He:SF_6 gas mixtures. With the obtained values the equilibrium electric field strength E/N for the positive column of the discharge was calculated. In a 20% SF_6/80% He mixture the electric field rises linearly with a slope of about 1 (kV/cm)/Tesla. Besides steady-state characteristics the transient dynamic response of the positive column to the change of the magnetic field was calculated. A typical time scale for the plasma response is tens of nanoseconds. To study magnetically controlled discharges experimentally a coaxial discharge system was built which allows application of axial magnetic fields up to 1.2 Tesla. Measurements of the discharge voltage and current in an 80% He 20% SF_6 mixture at a pressure of 8 Torr were performed at varying magnetic field intensities. The discharge voltage was found to increase with increasing magnetic field as predicted by our model. The quantitative agreement between theory and experiment is good for current densities approaching 1 A/cm^2.

The experimentally observed rise in discharge resistance with transverse magnetic fields demonstrates that magnetically controlled discharges have the potential for opening switches operating in a field strength range in excess of 1 kV/cm at current densities above 1 A/cm^2. The computed response time of the plasma to changes in the magnetic field indicates that these switches can be operated in the submicrosecond range at high repetition rates. Moreover the ability to control such discharges could lead to other important applications, such as magnetic control of reaction rates in gas discharges for semiconductor processing.

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INTRODUCTION

Low pressure diffuse discharge switches, operated close to the Paschen minimum, are characterized by low erosion rate and fast recovery. The charge carrier balance is generally determined by electrode as well as gas phenomena. With increasing pressure, however, electron molecule interactions in the gas define the discharge characteristic more and more. In the p*d (pressure times gap distance) range to the right of the Paschen minimum it should therefore be possible to control the resistance of the gas discharge through manipulation of the electron generation and depletion processes in the gas and the charge transport parameters. A way to change rate and transport coefficients in the low pressure range is through magnetic fields. Magnetic fields applied perpendicular to the electric field in the discharge shift the electron energy distribution $f(\varepsilon)$ towards low energies. The rate and transport coefficients are determined by the integral of the product of $\varepsilon^{1/2}*f(\varepsilon)$ and the cross sections for the processes being considered. It should therefore be possible to increase the resistance of glow discharges in gases with appropriate cross sections through application of magnetic fields. Applications for this effect are in the field of opening switches for inductive energy storage and as means to shorten the recovery time in low pressure closing switches operated at high repetition rates.

Glow discharges are spatially characterized by four regions: the cathode fall, the negative glow, the positive column, and the anode fall. The cathode fall voltage V_C is for large current densities ($j > 1$ A/cm^2) in the order of kilovolts over a distance of typically less than one millimeter (abnormal glow) (19). Voltages across the negative glow and the anode fall are negligible. The voltage drop in the positive column, where the electric field strength E is constant, is dependent on the length of the column. Control of the abnormal glow discharge through magnetic control of the positive column generally requires discharges with large electrode distance d. Since this part of the discharge can be considered as a homogeneous plasma, a condition which allows the use of zero order codes for modeling, theoretical studies have concentrated initially on magnetic control of rate and transport properties in the positive column.

The conductivity in the positive column is given by the product of electron density and electron mobility, with ion contributions neglected. Both quantities are affected by the magnetic field. The decrease of mobility with increasing magnetic field intensity B is usually expressed by the following equation, where a constant collision frequency ν_c is assumed:

$$\mu_e = \frac{e}{m} \frac{\nu_c}{\nu_c^2 + (eB/m)^2} \qquad (1)$$

μ_e is the electron mobility for zero magnetic field intensity, e and m are the electron charge and mass, respectively. The effect of the magnetic field on the conductivity through its influence on the electron density is usually not considered as being essential. However, as will be shown, the change in electron density due to magnetic field controlled electron generation and depletion processes can affect the conductivity in a similar way as through changes in the mobility.

The concept for magnetically controlled reduction of electron density and consequent reduction of conductivity in the positive column of a glow discharge is based on the following considerations: The electron energy distribution in the positive column is shifted towards smaller electron energies when a transverse magnetic field is applied. This leads to a reduction of the ionization rate coefficient, which is given as:

$$k_i = \left(\frac{2}{m}\right)^{1/2} \int_0^\infty f\,(\varepsilon,\ E/N,\ B/N)\ \varepsilon^{1/2}\ \sigma_i(\varepsilon)\ d\varepsilon \qquad (2)$$

If electronegative gases with attachment cross section peaking at low energies are used, an increase in attachment rate should occur due to the shift in the electron energy distribution. The attachment rate coefficient is:

$$k_a = \left(\frac{2}{m}\right)^{1/2} \int_0^\infty f\,(\varepsilon,\ E/N,\ B/N)\ \varepsilon^{1/2}\ \sigma_a(\varepsilon)\ d\varepsilon \qquad (3)$$

This serves as an additional mechanism to reduce the electron density. The effect of the magnetic field on the carrier density n_e could in this case -- that means by using suitable electronegative gases -- be more effective in changing the conductivity of the positive column than the change in mobility from Eq. (1).

THEORETICAL STUDIES

Monte-Carlo calculations were performed to simulate the positive column of glow discharges with applied transverse magnetic fields in gas mixtures of He and SF_6 at 10 Torr. The gas mixture, which we have chosen for our studies, was 20% SF_6/ 80% He and 5% SF_6/ 95% He, respectively, at 10 Torr pressure. The sulfur hexafluoride (SF_6) was chosen as the attacher for this work because of its strong attachment peak at very low energy, and the fact that its total set of collisional cross sections are more readily found than those for other candidate gases with similar attachment cross sections. There are several sources for SF_6 data (1-13). For the first calculations data compiled by Kline (1) were used. The results of these calculations are published in our paper on "Magnetic Control of Diffuse Discharges" (Appendix). Our more recent calculations were based on SF_6 cross sections provided by A. Phelps (2). Even though there were differences in the two sets of cross sections, the computed electron energy distributions in the positive column are almost identical. The cross sections for He, which serves as buffer gas, were taken from a paper by Hayashi (14).

1. Steady State Characteristics of the Positive Column

When describing the steady-state characteristics of the positive column, spatial uniformity of electric and magnetic field intensity was assumed. A Monte-Carlo code was used to calculate the electron-energy distribution, ionization rate coefficient, the attachment rate coefficient, the collision frequency and the drift velocity in a gas mixture of 20% SF_6 and 80% He. Because of the steady-state situation and the homogeneity of the gas and the applied fields, it is sufficient to simulate the motion of one single electron. From ergodicity it can be assumed that a sufficiently long path of this sample electron will give information on the behavior of the entire electron gas. Each run of the program considered 10^6 collisions. The range of the reduced electric field E/N investigated was 60 to 2400 Td and the range of magnetic flux density B was from 0 to 9 Tesla.

Results of these calculations, obtained with Kline's set of cross sections (1), are shown and discussed in the paper on "Magnetic Control of Diffuse Discharges" (Appendix). The ionization rate coefficient and the attachment rate coefficient, calculated by using Phelps' set of cross sections (2), are plotted in Fig. 1a and Fig. 1b, respectively. The collision frequency ν_c and the drift velocity v_d are shown in Fig. 2a and 2b as a function of reduced electric field with magnetic field intensity B as a parameter. The drift velocity shows the expected decay with increasing magnetic field, however, due to the reduction in collision frequency with B, the decay is not as strong as predicted by the simple model (see Eq. 1). The main effect of a magnetic field on the conductivity of our electronegative gas mixture seems to be the reduction of the effective ionization rate coefficient $(k_i - k_a)$ rather than the reduction of the mobility μ_e.

In order to determine the effect of SF_6 concentration in the buffer gas on the characteristics of the positive column, similar calculations as for 20% SF_6/ 80% He have been performed for 5% SF_6/ 95% He. Figures 3a and 3b show the ionization and attachment rate coefficient k_i and k_a for this gas mixture as a function of electric and magnetic field intensity. There is a strong effect of the magnetic field on the ionization rate coefficient in the entire range of electric field strength (0.4 to 4 1V/cm). The attachment rate coefficient, however, is strongly influenced by the magnetic field only at high electric field strengths.

The computed rate coefficients k_i and k_a can be used in a simplified continuity equation for electrons, where detachment, recombination and diffusion processes are neglected, to calculate the equilibrium reduced field strength E/N for the positive column of a discharge plasma as a function of B/N. This equilibrium E/N, or limiting E/N, is the electric field intensity at which

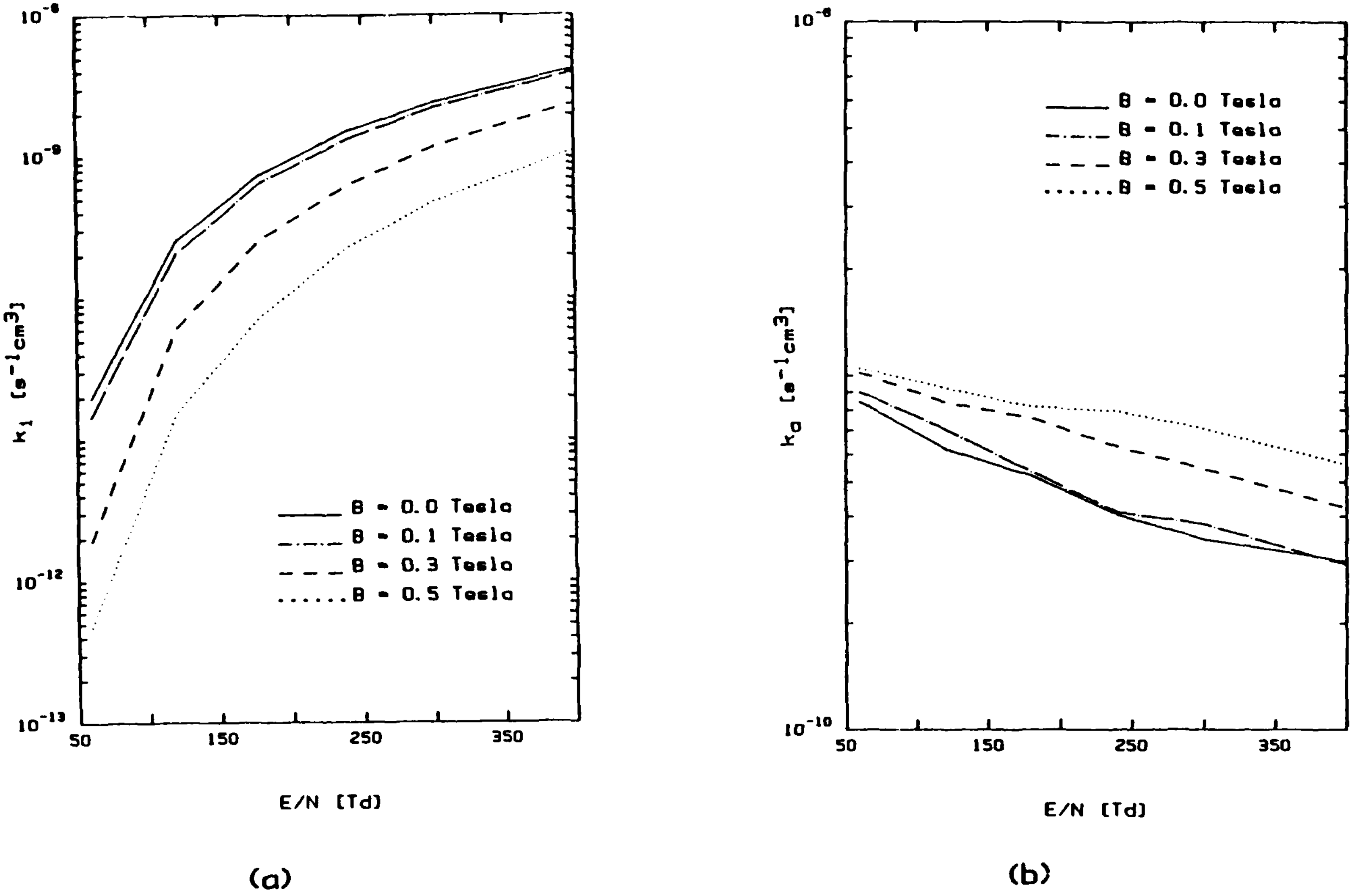

Fig. 1. Ionization (a) and attachment (b) rate coefficient as a function of E/N for various reduced magnetic flux densities, p = 10 torr, 20% SF_6 - 80% He.

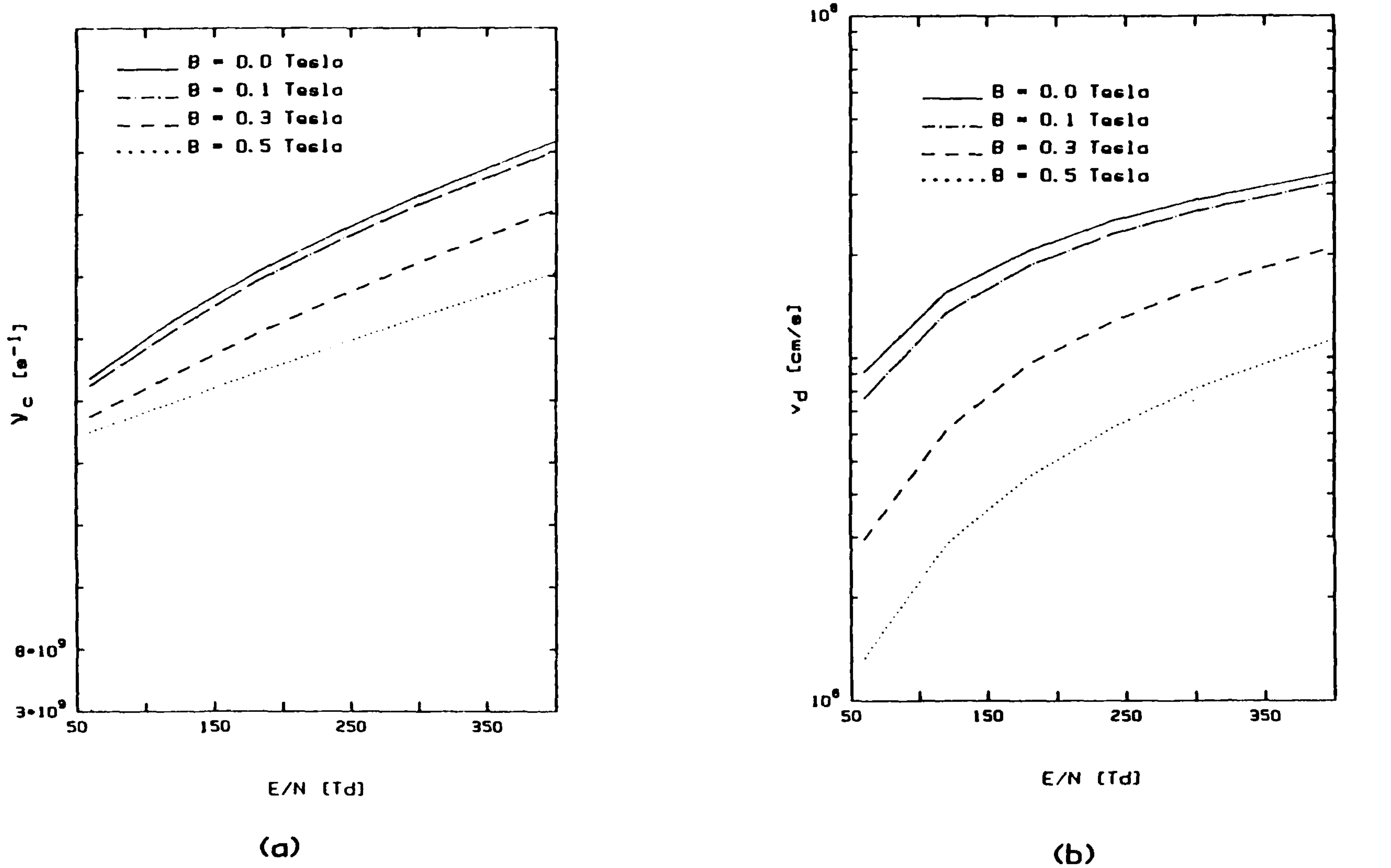

Fig. 2. Collision frequency (a) and drift velocity (b) as a function of E/N for various reduced magnetic flux densities, p = 10 torr, 20% SF_6-80% He.

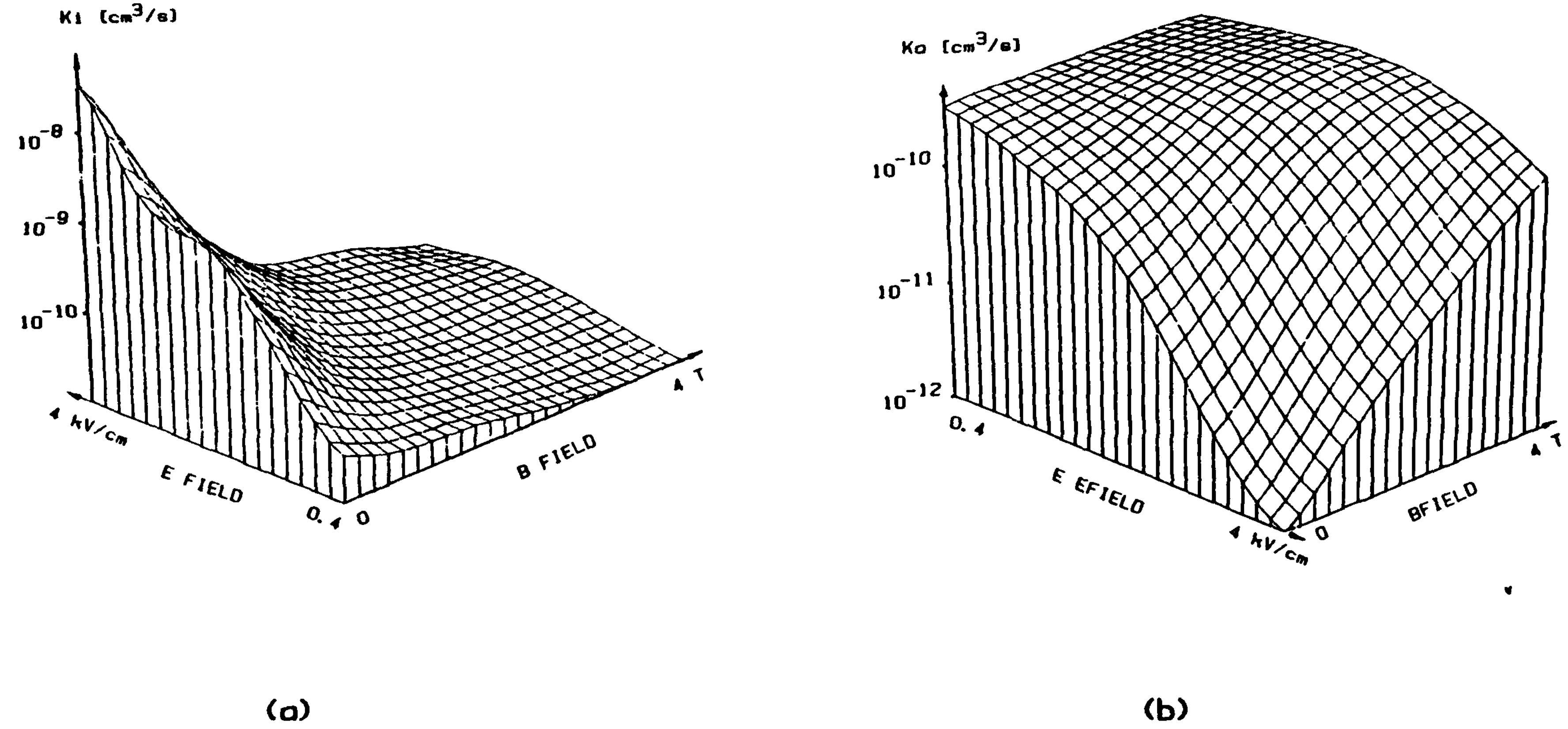

Fig. 3. Ionization (a) and attachment (b) rate coefficient as a function of E and B, p = 10 torr, 5% SF_6-95% He.

$$\frac{dn_e}{dt} = k_i \, N \, n_e - k_a \, N_a \, n_e = 0 \qquad (4)$$

The results from such calculations are shown in Fig. 4 for 20% SF_6/ 80% He and 5% SF_6/ 95% He. Except for small values of B/N, the E/N versus B curves increase linearly with a slope of $E/B \approx 1$ (kV/cm)/Tesla and ~ 0.25 (kV/cm)/Tesla, respectively. That means that the application of a magnetic field of 1 Tesla forces an increase of the voltage across the positive column of a glow discharge by 1 kV*d, where d is the length of the positive column, in order to sustain the discharge at a reduced current level. If the external electrical circuit does not allow the discharge voltage to rise, the discharge will be turned off by the magnetic field.

2. Transient Behavior of the Positive Column

To describe the temporal response of the positive column to the application of a transverse magnetic field a Monte-Carlo code was developed, where 10^4 electrons were simulated independently with appropriate distributions of initial conditions. The equilibrium electron energy distribution in the positive column at zero magnetic field was chosen to be the initial distribution. For a mixture of 20% SF_6/ 80% He this distribution occurs at E/N = 105 Td. At time t = 0 a step magnetic field was applied and the temporal development of the energy distribution of the initial 10^4 electrons was recorded until the distribution approaches the steady-state curve for the applied magnetic field with the electric field being constant. The temporal development of the electron energy distribution is shown in Fig. 5 for E/N = 105 Td and B = 0.5 Tesla * u(t), where u(t) is the unit step function.

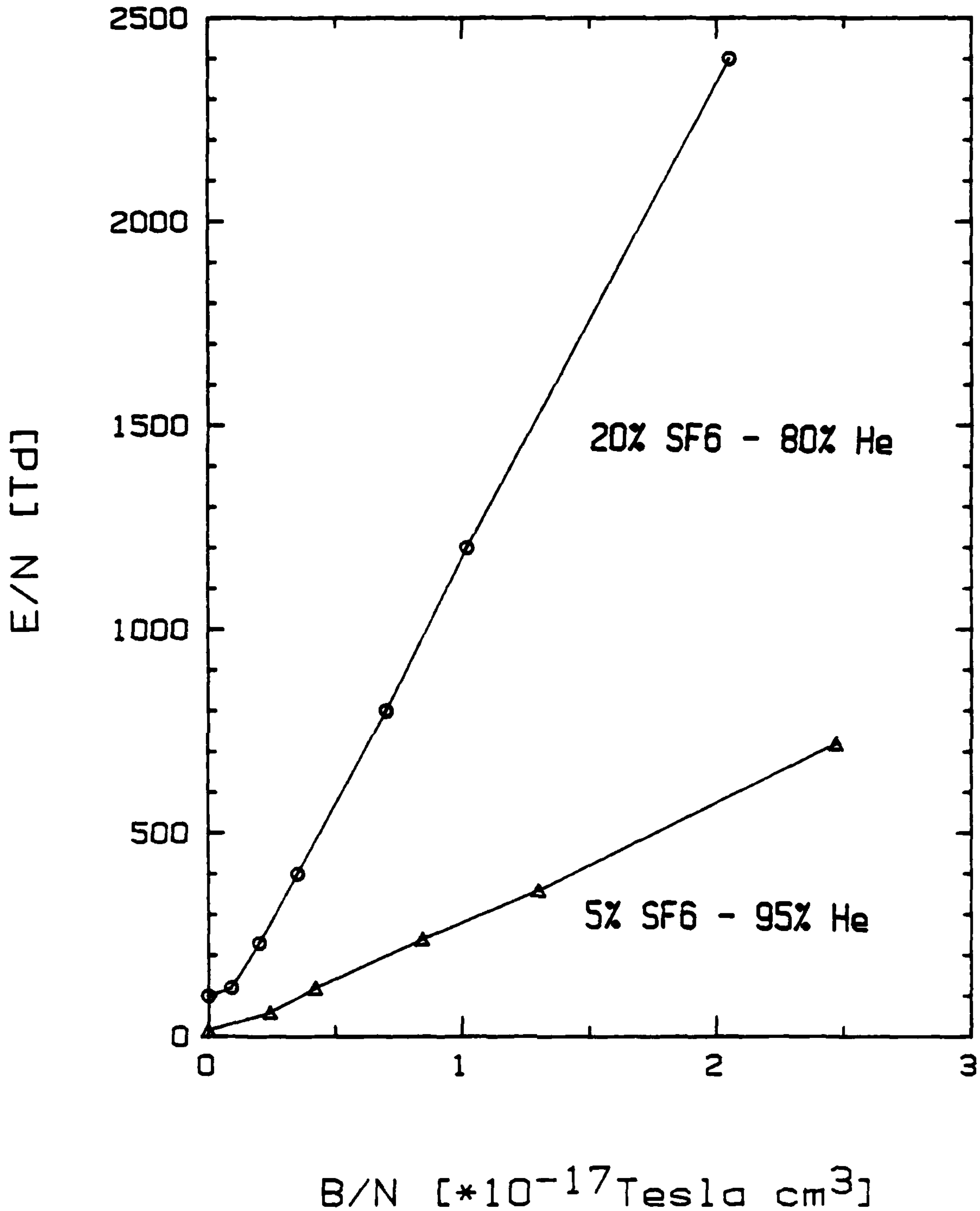

Fig. 4. Calculated positive column E/N as a function of reduced magnetic flux density B/N.

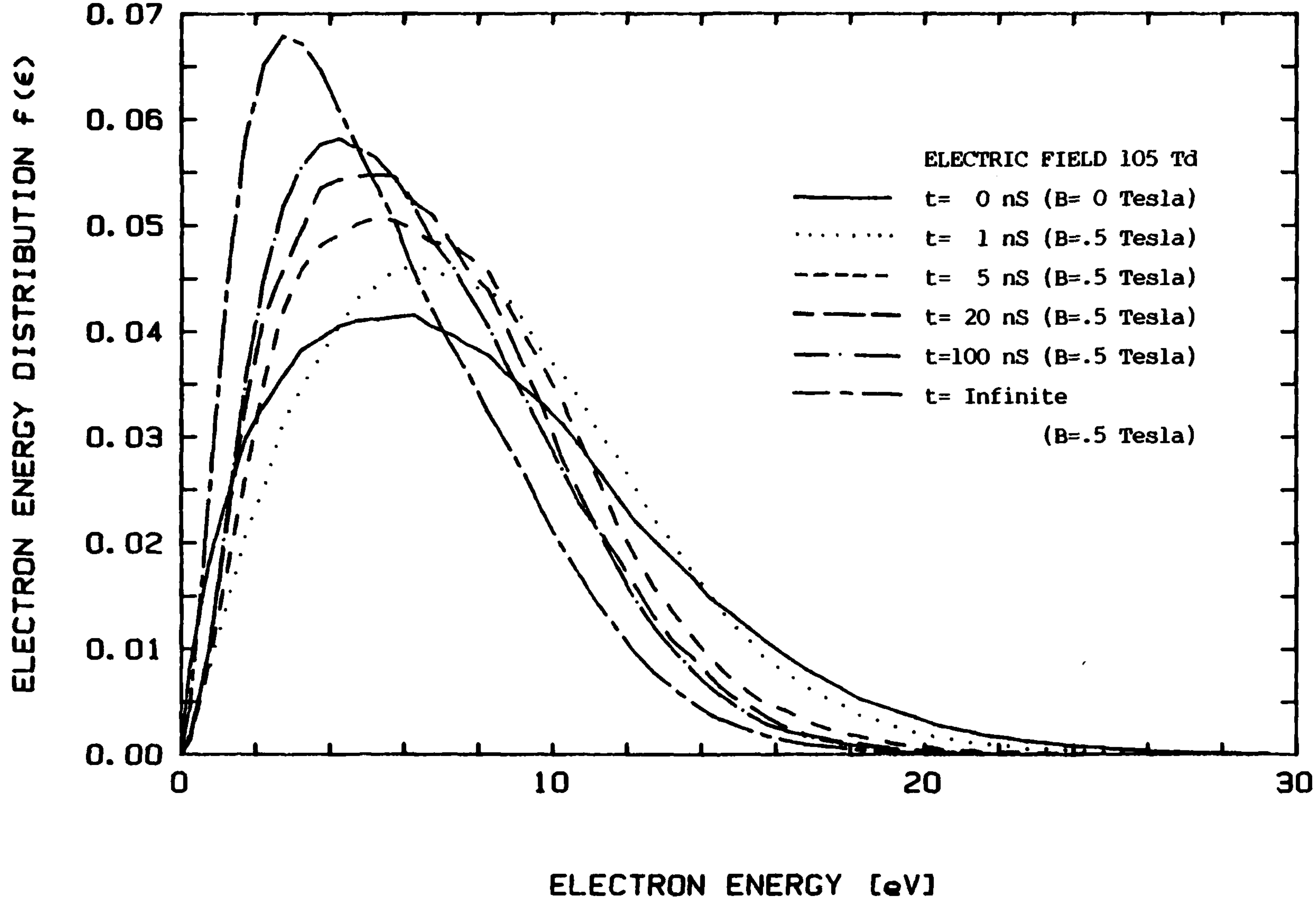

Fig. 5. Temporal change in electron energy distribution after application of a step magnetic field of B = 0.5 T u(t).

The temporal change of the ionization rate coefficient k_i and the attachment rate coefficient k_a for this case is shown in Fig. 6. The rate coefficient for attachment is multiplied by the ratio of attaching gas density N_a to total gas density N to allow direct comparison between electron generation and depletion rates in this gas mixture. At $t = 0$, k_i and k_a*N_a/N are equal. During the first nanosecond they both decrease by the same amount, then, however, the two curves approach different steady-state values. The reduced attachment rate coefficient is larger than the ionization rate coefficient by about a factor of two. The temporal development of the electron density can be estimated using the simplified continuity equation (4):

$$\frac{dn_e}{dt} = N(k_i - \frac{N_a}{N} k_a) n_e \qquad (5)$$

For steady-state values of k_i and k_a this differential equation can be integrated analytically and the result is

$$n_e = n_0 \exp [N(k_i - \frac{N_a}{N} k_a) t] \qquad (6)$$

This theoretical result corresponds to an experiment where the voltage across the discharge is kept at a constant value after the magnetic field is applied. This is the situation which is characteristic of capacitive discharge circuits. Consequently in a capacitive discharge circuit a 10 Torr, 20% SF_6/ 80% He glow discharge used as a switch should turn off with a time constant of $\tau \sim 100$ ns when a magnetic field of 0.5 Tesla is applied.

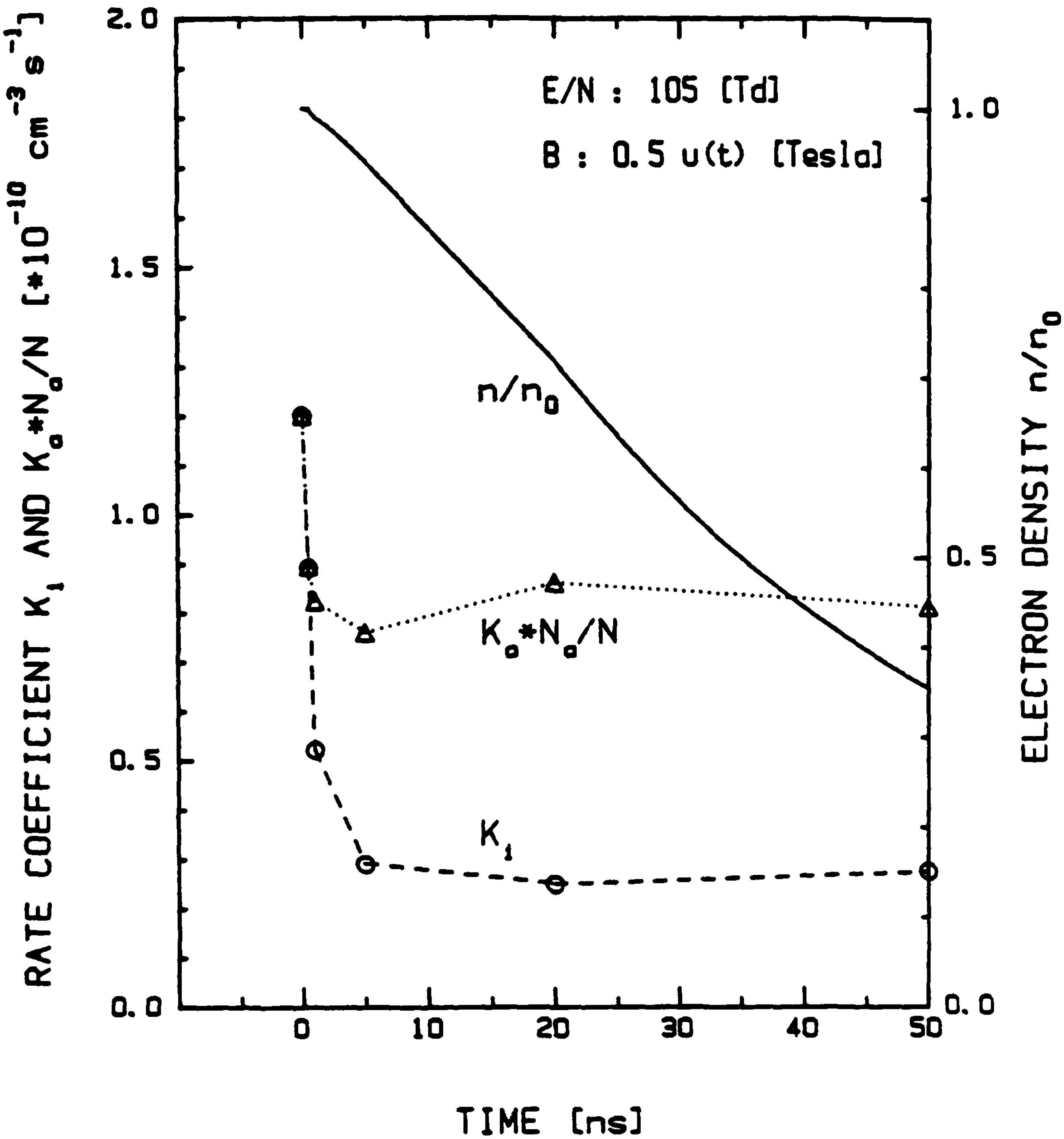

Fig. 6. Computed temporal change of ionization and reduced attachment rate coefficients k_i and $k_a \times N_a/N$, respectively, and the corresponding decay in normalized electron density n/n_0 after the application of a step magnetic field to an ionized gas (80% He:20% SF_6) at time T=0. (N_a: number density of SF_6, N: total number density).

3. Steady State Characteristics of the Cathode Fall

In order to reach current densities in excess of 1 A/cm^2, values which are desirable for pulsed power applications, the discharge has to be operated in a range which is characterized by large values of the cathode fall voltage V_c. To study the influence of magnetic fields on the cathode fall, we have developed a Monte-Carlo code which allows us to calculate the electron energy distribution in this region as a function of position. In a first approximation data were used which are characteristic for normal cathode falls, a region for which Monte-Carlo calculations have already been performed (15, 16), however, not for crossed electric and magnetic fields. As in these studies the cathode fall distance d_c was assumed to be 1 cm, and the cathode fall voltage V_c was set to 400 V, with the electric field decreasing linearly from cathode to the negative glow region. The energy distribution function of the electrons leaving the cathode was assumed to be constant between 0 and 10 eV, and zero for higher energies (17). Ensembles of 500 initial electrons were used to simulate the cathode fall. The program was repeated twenty times to achieve a reasonable accuracy in electron energy distribution and transport coefficients.

Results for 0 and 0.5 Tesla are shown in Fig. 7a and 7b, respectively. The effect of the magnetic field on the electron energy distribution is almost negligible in the vicinity of the cathode. However, it becomes very pronounced in the region adjacent to the negative glow. Here the number of high energy electrons is greatly reduced by the magnetic field. Consequently, the effective ionization coefficient is lower in this region, which causes the cathode fall voltage to rise in order to sustain the discharge.

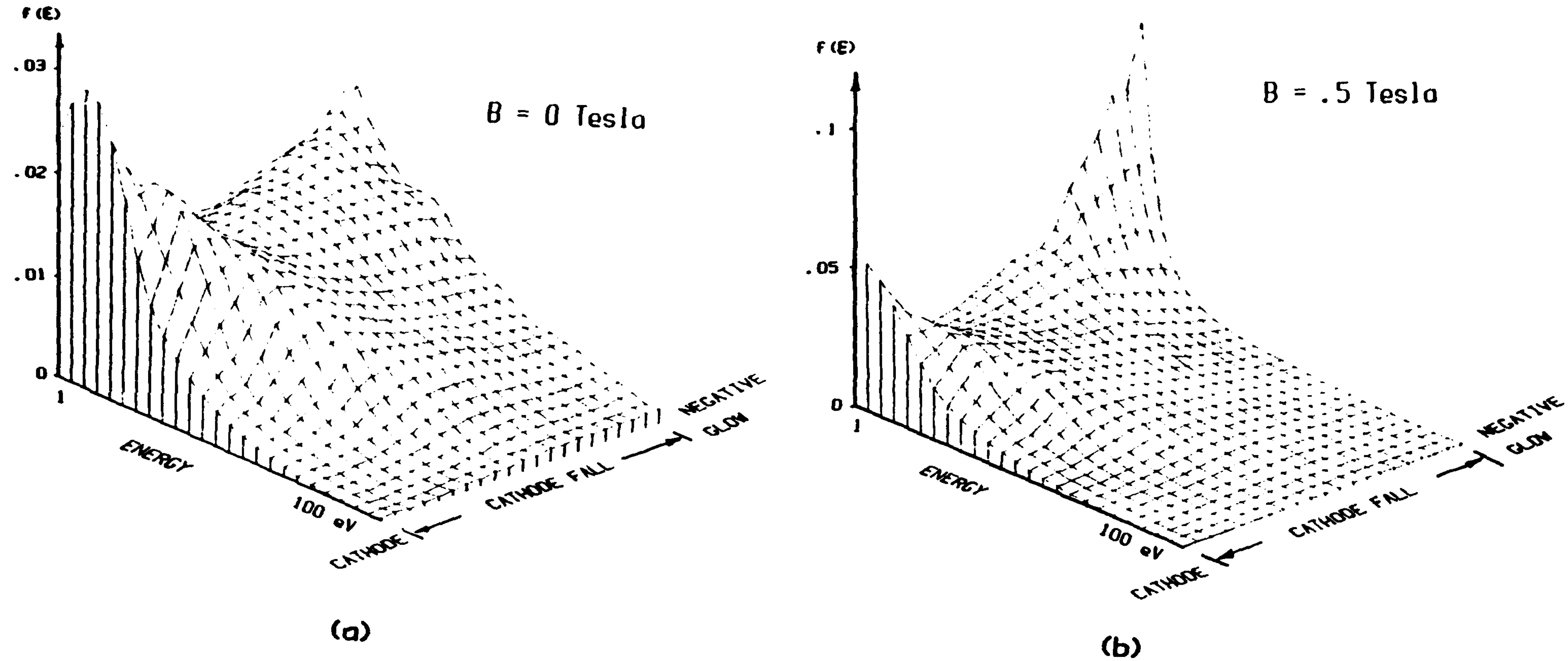

Fig. 7. Computed electron energy distribution in 20% SF_6-80% He (p = 10 torr) as a function of position in the cathode fall. (a) B = 0.0 Tesla (b) B = 0.5 Tesla.

EXPERIMENTAL STUDIES

1. Experimental Setup

The experimental setup is described in the paper on "Magnetic Control of Diffuse Discharges" (Appendix). The diagnostic system has been improved. Besides monitoring the current it is now possible to record the voltage simultaneously, using the recently acquired fast digitizers (Tektronix 7912 AD). The voltage probe consits of a capacitive divider, integrated in the coaxial discharge system, with a resistive divider in series. The voltage divider ratio is 62000.

2. Experimental Results

The electrical characteristics of glow discharges in transverse magnetic fields were measured in a 20% SF_6/ 80% He mixture. The pressure was 8 Torr, well to the right of the Paschen minimum value. The measured Paschen curve for the gas mixture is shown in Fig. 8 together with that for pure He. Current and voltage traces for a discharge at B = 1.2 Tesla are shown in Fig. 9. When the spark gap in the discharge circuit breaks down, a large voltage is applied to the discharge chamber. After it reaches the breakdown value, the voltage drops and the current rises rapidly. After a current overswing and a corresponding dip in the voltage the current and voltage approach in some tens of nanoseconds a steady state. The resistance in this phase is about 30 ohms. For most shots the duration of this phase is not determined by the discharge circuit (200 ns transmission line) but by transition into an arc. The onset of the glow-to-arc transition varies statistically, but generally it becomes faster with increasing magnetic field. The strong variations of voltage and current at about 200 ns after

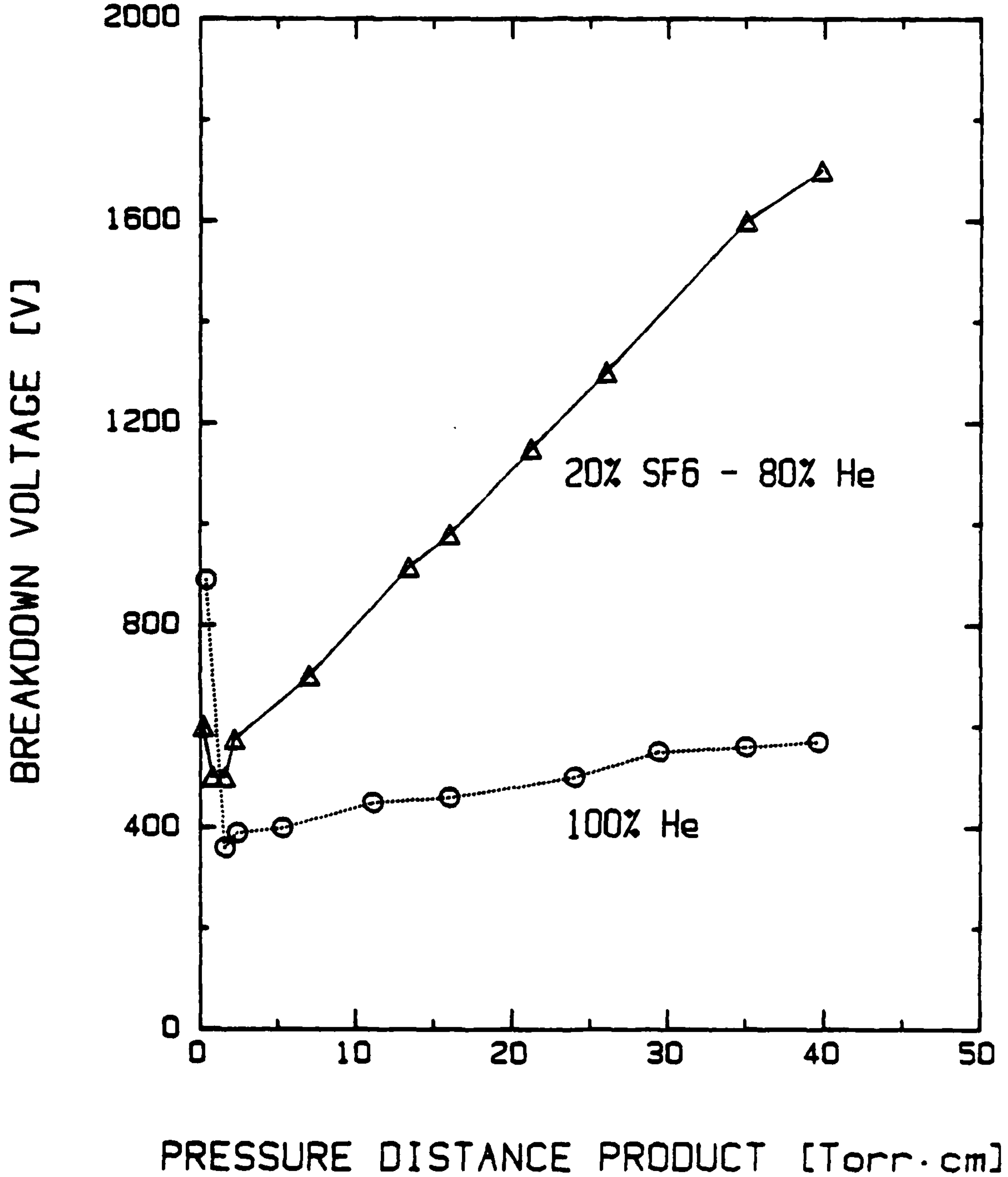

Fig. 8. Paschen curve for 100% He and 20% SF_6-80% He. (electrode material: brass).

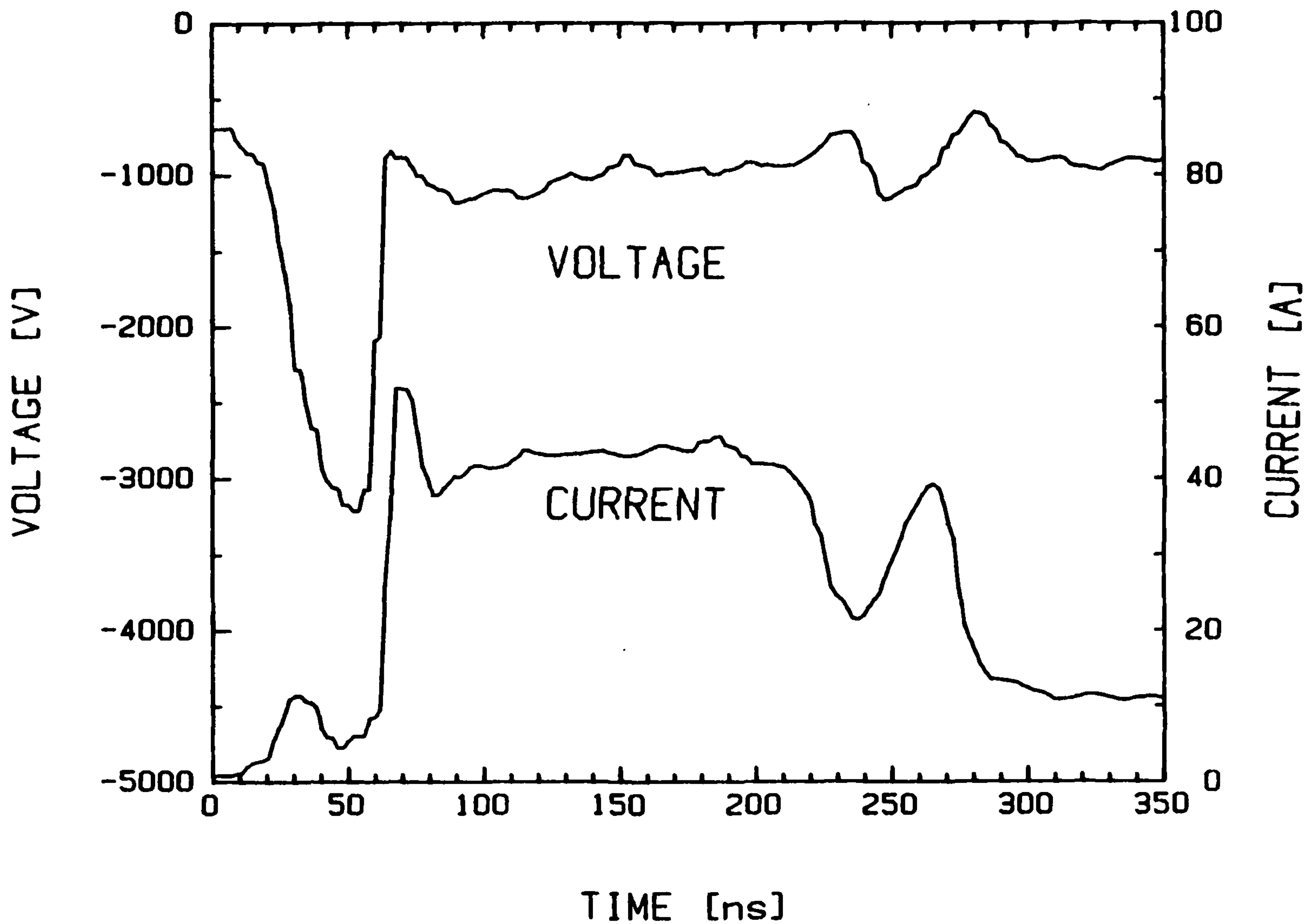

Fig. 9. Temporal development of the voltage and current in a 20% SF_6-80% He discharg at 8 torr with an applied transverse magnetic field of 1.2 Tesla.

breakdown are caused by reflections of the spark gap trigger pulse. This temporal behavior is typical for discharges in transverse magnetic fields above 0.1 Tesla. For small magnetic fields and large currents (150 A) a discontinuity in the discharge current was observed and by using circuit data it was concluded that this corresponds to a voltage discontinuity (Fig. 7, Appendix). Voltage measurements, however, have yet to confirm this conclusion.

The current-voltage characteristics for 80% He/ 20% SF_6 with the magnetic field strength as parameter is plotted in Fig. 10. The dots represent experimental values with an error of about 10%, due to the uncertainty in voltage data. According to our simple model for the positive column (Eq. 4), E/N and therefore also the voltage -- at least in the positive column -- should not depend on the current. This is approximately true for low values of magnetic field intensity. At higher magnetic field strengths, however, there is a distinct increase of voltage with increasing current. This effect might be due to the increasing importance of recombination processes at higher magnetic fields, processes which so far have been neglected in our model.

The voltage is rising with increasing magnetic field as expected from our theoretical studies. Besides this qualitative correspondence there is a reasonable agreement of theory and experiment what the rate of change of electric field with increasing magnetic field concerns. In Fig. 11 the theoretical E/N versus B/N curve is compared with curves derived from experimentally obtained values at currents of 60 A and 100 A. For these curves it was assumed that the positive column extends over the entire distance between the electrodes and that E/N is constant in this region. The agreement in the slopes of experimentally and theoretically obtained E/N

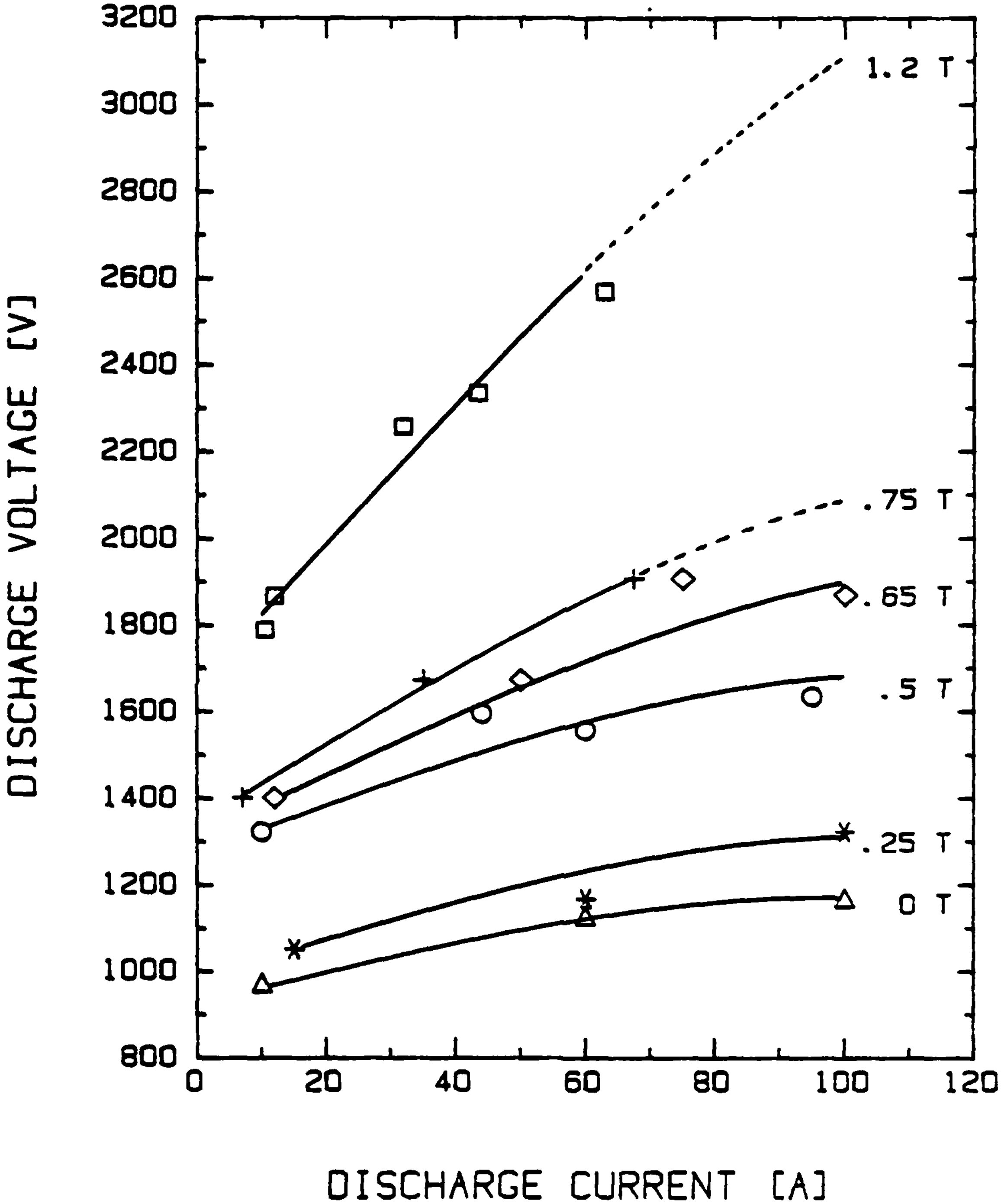

Fig. 10. Voltage current characteristics for a glow discharge in 20% SF_6-80% He at 8 torr with magnetic field strength as a parameter.

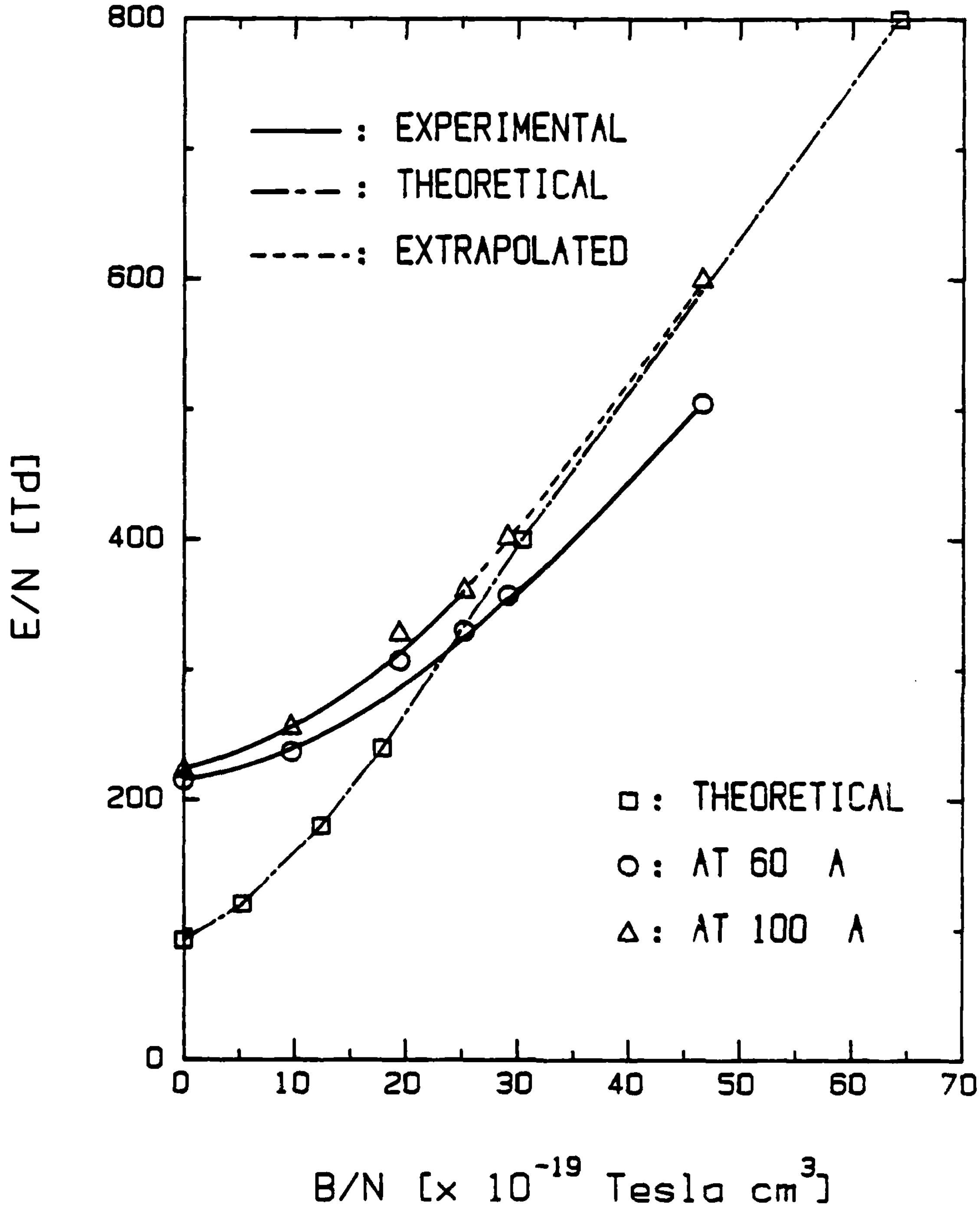

Fig. 11. E/N values as a function of magnetic field strength for current densities of 0.6 A/cm^2, 1.0 A/cm^2 (60 A and 100 A) and the computed curve which is independent of current density. The experimental values were deduced from the voltage current characteristics assuming that the electric field is uniform over the length of the discharge.

versus B/N curves seems to become better with increasing current density.

Discharges in pure He show the opposite tendency in the current voltage characteristics than discharges in SF_6/He. The discharge voltage decreases with increasing magnetic field. This does not agree with the consideration for the positive column. For this part of the discharge we would expect an increase in electric field even in gases without attachment. The decrease in voltage is therefore determined by processes in the cathode fall region. For He the cathode fall is, according to our measurements, dominating the voltage distribution along the axis of the discharge.

CONCLUSIONS AND CONSEQUENCES

1. Experiment

The experimental results show that in SF_6/He glow discharges the discharge impedance increases when a transverse magnetic field is applied. The rate of change in voltage with magnetic field intensity at magnetic fields above .3 Tesla, in our system, approaches the value 2 kV/Tesla, a value which we assume can be increased linearly by increasing the geometric length of the discharge.

A problem which imposes restraints to the use of magnetically controlled discharges as switches is the relatively high forward voltage at zero magnetic field, which in our system is greater than 1 kV and is increasing with current density. A considerable contribution to this voltage comes from the cathode fall. There are several ways to reduce the cathode fall without sacrificing current density, including the use of cathodes with higher secondary Townsend coefficients, thermionic cathodes, and hollow cathodes. Of these, hollow cathodes (18) seem to be easiest to integrate in our present discharge. It is therefore planned to build a small planar discharge chamber which will allow the investigation of cathodes for abnormal glow discharges.

A second problem for the use of abnormal glow discharges as switches is the rapid transition from glow to arc with increasing magnetic field and corresponding increasing discharge voltage. It is assumed that the instabilities which lead to the termination of the current flow have their origin in the cathode fall, the discharge region with the highest electric field strength. In order to study the onset of these instabilities, optical diagnostics of the discharge by means of an image-converter camera with 10 ns shutter time is planned.

So far the discharge has been operated in a semistatic magnetic field with a pulsed electric field applied. This method of operation allows the steady-state characteristics of glow discharges in crossed fields to be found using a relatively simple experimental setup. In order to determine the discharge behavior when used as an opening switch, the discharge must be operated in a semistatic electric field, and the magnetic field has to be applied in a pulsed mode. A system is under construction which will allow the application of pulsed magnetic fields up to 1 Tesla with a rise time of about 200 ns.

2. Theory

Theoretical investigations of the positive column in a magnetically controlled glow discharge in 20% SF_6/80% He have been performed, both steady-state and time-dependent. The steady-state calculations indicate that a magnetically induced increase in electric field strength [of about 1(kV/cm)/Tesla], corresponding to an increase in resistance, can be expected. This result is in reasonable agreement with our experimental observations (Fig. 11). The positive column model does not give the absolute value of the discharge voltage. At current densities in excess of 1 A/cm^2, corresponding to currents greater than 100 A in our system, it is expected that the voltage across the discharge is determined more and more by the cathode fall rather than the positive column [19]. Therefore, and because of the importance of this region for the stability of the discharge it is planned to expand the theoretical investigations of the cathode fall by developing a self consistant model of the cathode region in crossed electric and magnetic fields.

The time-dependent investigations of the positive column gave an estimate of the time scale of the dynamic response of the plasma to changes in the magnetic field for a constant electric field. In order to model the transient behavior of an opening switch in an inductive energy storage system the influence of the circuit parameters on the electric field have to be considered. As a next step in the theoretical description of the glow discharge as a switch it is planned to model the discharge as part of an inductive circuit by means of rate equations and circuit equations, with time dependent rate coefficients obtained with a first order Monte-Carlo code for the positive column.

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APPENDIX

MAGNETIC CONTROL OF DIFFUSE DISCHARGES

by

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MAGNETIC CONTROL OF DIFFUSE DISCHARGES

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Abstract - By application of a crossed magnetic field, the electron energy distribution in a gas discharge can be shifted to lower energy values, as demonstrated by means of Monte Carlo calculations for electrons in $He:SF_6$ mixtures. Consequently, through the change in the rate coefficients for ionization and attachment, the sustaining field in the discharge plasma is increased. This magnetically induced voltage rise was studied in a low-pressure glow discharge. The cathode fall was found to be the dominant component in determining the characteristics of this magnetically controlled discharge. The drastic rise of the cathode fall above a threshold value could be utilized in operating a glow discharge as an opening switch for an inductive energy storage system.

I. INTRODUCTION

Low-pressure diffuse discharges have been studied extensively with respect to their application as closing switches. Examples of switching devices operating at low pressures are thyratrons [1], tacitrons [2], and crossatrons [3]. Common to all these devices is their operation on the low pd side of the Paschen minimum, with p being the gas pressure and d the electrode spacing. The application of crossed magnetic fields in this pd range leads to a decrease in breakdown strength and plasma resistivity in the on state of a switch, an effect which has been successfully used in operating crossed field tubes as closing switches.

If the gas pressure is such that pd is on the high side of the Paschen minimum, the application of a crossed magnetic field has the opposite effect. In this pd range, where the characteristic of the discharge is determined by electron-molecule collisions, rather than by electrode (γ) processes, the applied magnetic field causes a change in the transport properties of the discharge such that an increase in both breakdown field strength [4] and resistivity [5] occurs. This effect provides a means for the use of magnetically controlled low-pressure discharges as opening switches.

II. THEORY AND COMPUTATIONAL RESULTS

The application of a magnetic flux density $\vec{B}$, which is transverse to the electric field $\vec{E}$ in the discharge, changes the transport parameters of the electrons by changing the electron energy distribution $f(\varepsilon)$. This was demonstrated by means of Monte Carlo calculations in pure SF_6. Fig. 1 illustrates this shift in the distribution function for a mixture of He and SF_6. These data were generated again by Monte Carlo calculations [7]. The cross sections for this calculation for He were taken from a paper by Hayashi [8] and those for SF_6 were taken from Kline [9]. The electron scattering was assumed to be isotropic. The major points of interest in the crossed field induced changes in $f(\varepsilon)$ are the reduction in the high-energy tail of the distribution and the shift of the mean energy to lower values with increasing reduced magnetic flux density B/N, N being the number density of the gas molecules. The mean energies for the $B/N = 0$ and $B/N = 1.5 \times 10^{-18}$ T • cm^3 distributions are 11.6 and 8.0 eV, respectively.

The effect on the tail of $f(\varepsilon)$ can be explained by considering the electron trajectories in crossed electric and magnetic fields. The electrons that make up the high-energy part of the electron energy distribution in a gas with an electric field only are those which have been forward scattered, i.e., scattered in the direction of the electric field lines. The forward-scattered electrons in a crossed field discharge travel paths that are curved due to the $\vec{v} \times \vec{B}$ forces acting on the particle. This means that forward-scattered electrons will not gain as much energy as in the "electric-field-only" case, so the high-energy tail of the electron energy distribution is reduced. The shift in the mean energy has been derived both analytically [10] and in computer simulations [5], [11] for crossed field discharges.

The changes in the distribution function significantly affect the electron transport parameters of a discharge in a gas mixture of 20-percent SF_6 and 80-percent He, as shown by the plots of ionization and attachment rate coefficients in Figs. 2 and 3, respectively. These data were generated by counting the number of ionization and attachment processes with the same Monte Carlo calculations as were used to produce the distribution functions of Fig. 1. Rate coefficients in a gas are defined by the equation

$$k_j = \left(\frac{2}{m_e}\right)^{1/2} \int \sigma_j(\varepsilon)\ \varepsilon^{1/2}\ f(\varepsilon)d\varepsilon \qquad (1)$$

where k_j is the rate coefficient, $\sigma_j(\varepsilon)$ is the corresponding collision cross section, m_e is the electron mass, and ε is the electron energy. In Fig. 2 it can be seen that the ionization rate coefficient k_i is reduced by more than three orders of magnitude by the application of a magnetic field of $B/N = 1.5 \times 10^{-18}$ T • cm^3 for 20-percent SF_6 and 80-percent He. The attachment rate coefficient k_a is strongly affected by the magnetic field only below some threshold value. For E/N = 2400 Td, this threshold is at $B/N = 6 \times 10^{-18}$ T • cm^3, as shown in Fig. 3. The rate coefficient remains fairly constant above this value of B/N. This behavior is typical for an attacher whose attachment cross section peaks at low energies, such as SF_6 [9]. The drift velocity υ_d for a particular E/N is also reduced if a transverse magnetic field is present. This is due to the lowered electron mobility in the electric field direction caused by the gyrating path of the electrons in crossed fields.

The computed rate coefficients k_i and k_a can be used in the continuity equation for electrons to calculate the equilibrium E/N for the positive column of a discharge plasma as a function of B/N. This equilibrium E/N, or limiting E/N, is the electric field intensity at which

$$dn_e/dt = k_i N n_e - k_a N_a n_e = 0. \quad (2)$$

The results from such a calculation for a 20-percent SF_6-80-percent He gas mixture are shown in Fig. 4. Except for small values of B/N (<0.1 x 10^{-17} T • cm^3), the E/N versus B/N curve increases linearly with a slope of $E/B \sim 1$ kV/(T • cm).

III. EXPERIMENTAL RESULTS

Experimental studies of low-pressure glow discharges in crossed electric and magnetic fields were performed with the apparatus shown in Fig. 5. The discharge is produced by overvolting a coaxial gap whose dc breakdown voltage in 8 torr of 20-percent SF_6-80-percent He is approximately 2 kV. The brass center conductor is the cathode, which has a diameter of 3.18 cm and a surface area of 100 cm^2. The anode is a set of twelve 0.32-cm-diameter stainless steel rods arranged to form a cylinder around the cathode. The anode-cathode gap spacing is 2.06 cm at the minimum point. The spacing between the rods allows the magnetic field to permeate the discharge with a time constant determined by the plasma conductivity. The discharge can be driven by either a 50-Ω, 1-μs Pulse Forming Network (PFN) or by a section of 50-Ω cable and is switched by a midplane triggered spark gap using a krytron trigger circuit. The discharge system, which is matched to

50 Ω, is designed to deliver voltage pulses of up to 40 kV to the discharge chamber with rise times on the order of nanoseconds.

The magnetic field is applied axially to the discharge chamber by a coil which is driven by a 20-kV capacitor bank. The total capacitance of this bank is 45μF, the inductance of the magnetic field coil, which is wound on a form and placed around the discharge chamber, is 970 μH, and the circuit is overdamped to prevent voltage reversals on the capacitors. The current is switched to the coil through a spark gap. Magnetic flux densities of up to 0.8 T can be obtained with this circuit. The time scale of the pulse is such that the magnetic field strength is constant for the duration of the glow discharge. Timing for the system is accomplished by picking off a portion of the magnetic field coil current to trigger a delay generator which in turn fires the krytron trigger pulser and initiates the discharge. The delay can be adjusted so that the discharge occurs during the time when the magnetic flux density is at its desired level. The discharge current was measured with a Rogowski coil, and the total discharge voltage was calculated using this measured current and transmission line data.

The effect of the magnetic field on the discharge impedance is strongly dependent on the pressure range where the discharge is operated. Results of impedance measurements with and without magnetic field over a pressure range from 0.5 to 7 torr are shown in Fig. 6. Below 5 torr, the application of a magnetic field causes the impedance to drop, a fact which is utilized in crossed field tubes [3]. Above approximately 5 torr, the discharge characteristics are determined by electron-molecule collisions as discussed previously. In this range, the impedance increases in crossed field configurations. Experiments attempted with a magnetic field at higher values of B/N lead to filamentary discharges with onset times on a nanosecond time scale.

The equilibrium voltage of the glow discharge with varying magnetic fields at a pressure of 8 torr in a 20-percent SF_6-80-percent He gas mixture is given in Fig. 7. The discharge current in this experiment was on the order of 150 A. The measured discharge voltage shows a linear increase with a slope of approximately 6 kV/T up to 0.02 T. Above this value of B, the voltage rises sharply with a slope on the order of 100 kV/T. At values above 4 kV further measurements were not possible due to the increasingly rapid glow-to-arc transitions at higher voltages, which lead to a sudden drop in discharge impedance.

Comparing the experimental values with computational results allows estimation of the cathode voltage drop in the glow discharge. We have assumed that the positive column extends over the entire distance between the electrodes and that E/N is constant in this region. Using the computed equilibrium values of the reduced electric field strength, the positive column shows a magnetic field dependence, as shown in Fig. 7. The difference between the measured voltage and the positive column voltage is the sum of the anode and cathode fall voltages. The cathode fall is typically the much larger of the two under the conditions of the experiment. Under these assumptions, the calculated cathode fall was found to be constant up to $B \sim 0.02$ T. Above this value it rises drastically, with a slope of approximately 100 kV/T. That means that above a certain magnetic field strength the total voltage seems to be primarily determined by fall processes for the range studied experimentally.

IV. DISCUSSION

From the computationally obtained values for the voltage drop across the positive column and the total discharge voltage, it is apparent that the cathode fall region strongly influences the discharge characteristics, both with and without an applied magnetic field. For $B = 0$, the cathode fall was found to be 1.5 kV, which is almost an order of magnitude higher than the values normally reported [12], [13]. This high value is typical for abnormal glow discharges, i.e., glow discharges whose current is so high that the current density at the cathode is determined by the area of the cathode rather than the external circuit parameters. Studies by von Engel [11] show that the abnormal cathode fall voltage is an increasing function of j_c/p^2, where j_c is the current density at the cathode and p is the gas pressure. This means that for abnormal glows the discharge is in a range of operation in which the V-I characteristic has a positive slope. For our experimental values, $I \sim 150$ A, cathode area $A_c = 100$ cm^2, and $p = 8$ torr, the value for j_c/p^2 falls well into the region of abnormal glow discharges for He. Since the pressure of SF_6 in the gas mixture contributes to the properties of the cathode fall as well, direct comparison to the von Engel data is not possible.

For $B \neq 0$, there is a sharp increase in voltage above a threshold value of $B = 0.02$ T. A qualitative understanding of the strong magnetic field dependence of the cathode voltage can be gained by observing the characteristics of the electron energy distribution of the cathode fall at $B = 0$. The electron energy distribution in the cathode fall in a normal glow at the edge of the negative flow region has been calculated by An et al. [14]. Their results show that a large number of electrons produced at the cathode do not collide in the cathode fall region, so that there is a peak in the distribution at an energy corresponding to the full cathode fall voltage. The characteristics of the electron energy distribution of an abnormal glow cathode fall should be similar except for the difference in energy caused by the higher cathode fall voltage. If a transverse magnetic field is applied, this high energy peak will be greatly reduced. In order to compensate for the resulting decrease in the ionization rate, the cathode fall voltage must increase.

If such a discharge is considered as a switch in an electric discharge circuit, the current will decrease with increasing magnetic field. This decrease in current will eventually turn the initially abnormal discharge into a normal one with reduced cathode fall. This means that at high magnetic field strengths the total hold off voltage of the switch will be determined mainly by the voltage across the positive column, rather than the cathode fall.

Whereas the sharp increase in discharge voltage at a threshold B/N is a desirable effect for an opening switch, the increasingly rapid transition from glow to arc with higher magnetic fields could impose certain restraints to the use of a magnetically controlled discharge as a switch. However, if operated as an opening switch, in which the magnetic field is applied after the discharge is fully established, rather than before breakdown (as in our experiment), the device should exhibit reduced arcing compared to the results previously discussed. A way to improve the discharge further with respect to its application as a switch is to reduce the strong electric field in the cathode region during the conduction phase ($B = 0$). Two types of cathodes which could help to achieve this end are the thermionic cathodes and hollow cathodes [15]. Both of these electrodes have the capability to produce high current densities while maintaining a lower forward voltage drop across the discharge.

The lower forward voltage drop not only aids in delaying the instabilities in the cathode region [16], but is also important for reduced power loading in the gas during conduction. The higher current density is necessary to achieve reasonable power gains in inductive energy storage systems with a magnetically controlled discharge as the opening switch. The power gain G can be defined as the power transferred into the load divided by the change in magnetic field energy necessary to generate an electric field $\overline{E_{max}}$ averaged over the axis of the discharge. For a resistive load of resistivity $\overline{E_{max}}/J$, G is on the order of

$$G = \frac{\frac{1}{2}\,(J\,\overline{E_{max}})}{\frac{d}{dt}\,(B^2/2\mu_0)} \tag{3}$$

Assuming that the discharge is biased at a static magnetic flux density B_0 just below the sharp increase in voltage with B (see Fig. 7), a drastic increase in electric field intensity can be obtained with rather moderate transient B fields on the order of 0.01 T. With opening times of approximately 0.1 μs, and electric field intensities of $\overline{E_{max}} \sim 1$ kV/cm, current densities of $J > 1$ A/cm^2 are required to obtain power gains in excess of unity.

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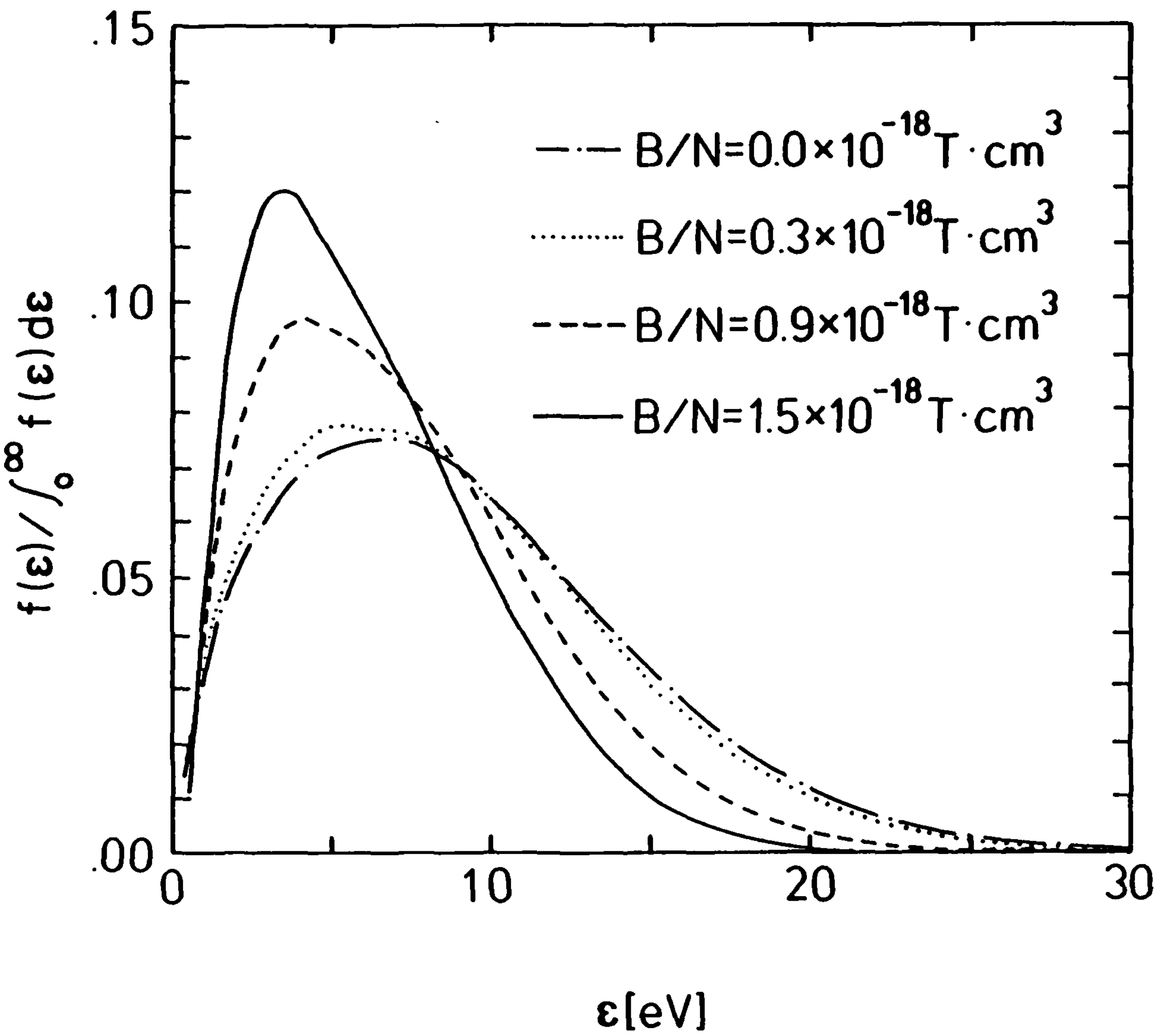

Fig. 1. Electron energy distributions for a reduced electric field strength of E/N = 120 Td in 20-percent SF_6-80-percent He for various values of reduced magnetic flux density B/N.

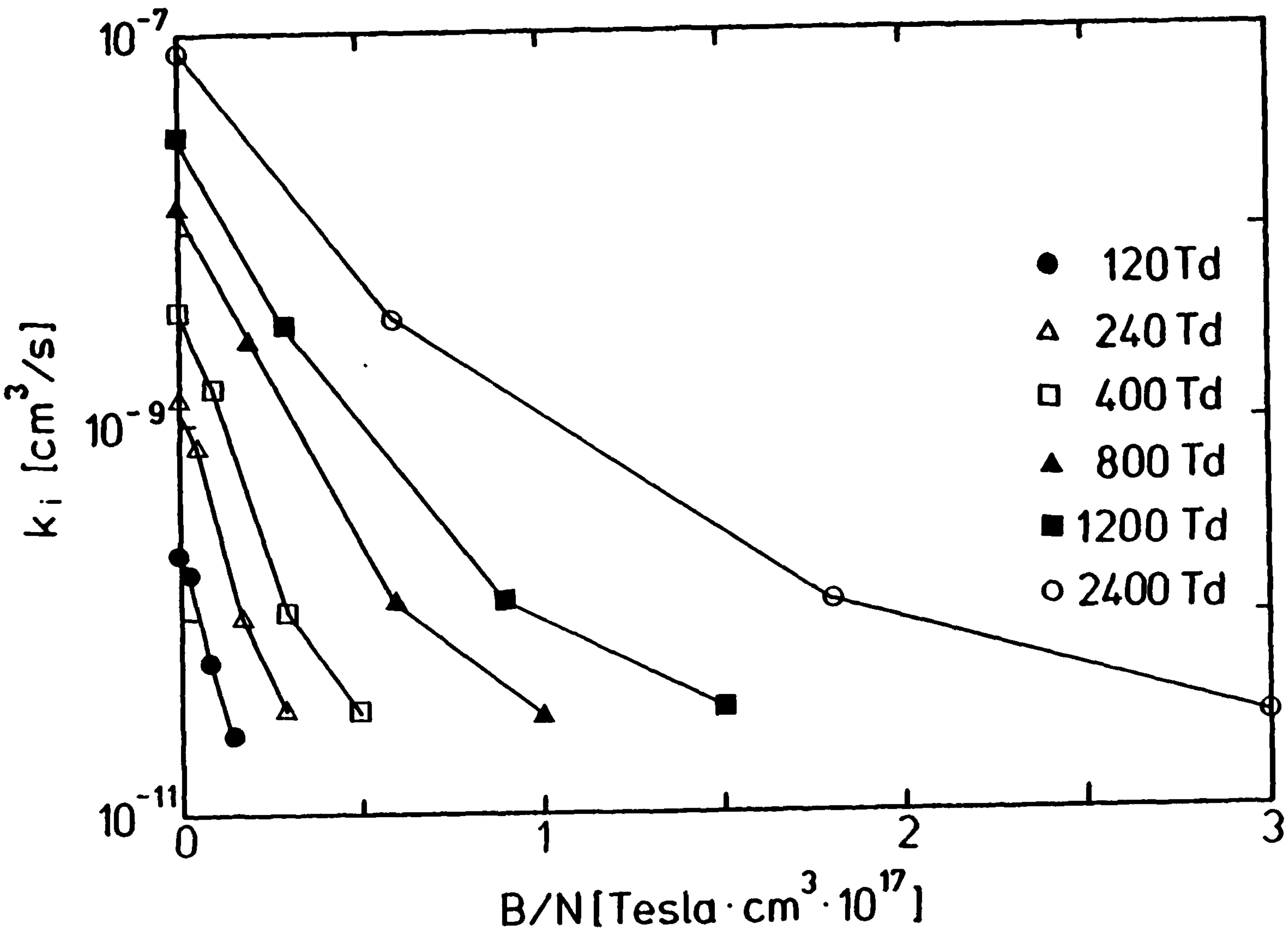

Fig. 2. Ionization rate coefficient k_i as a function of reduced magnetic flux density B/N with the reduced electric field strength E/N as a parameter in 20-percent SF_6-80-percent He.

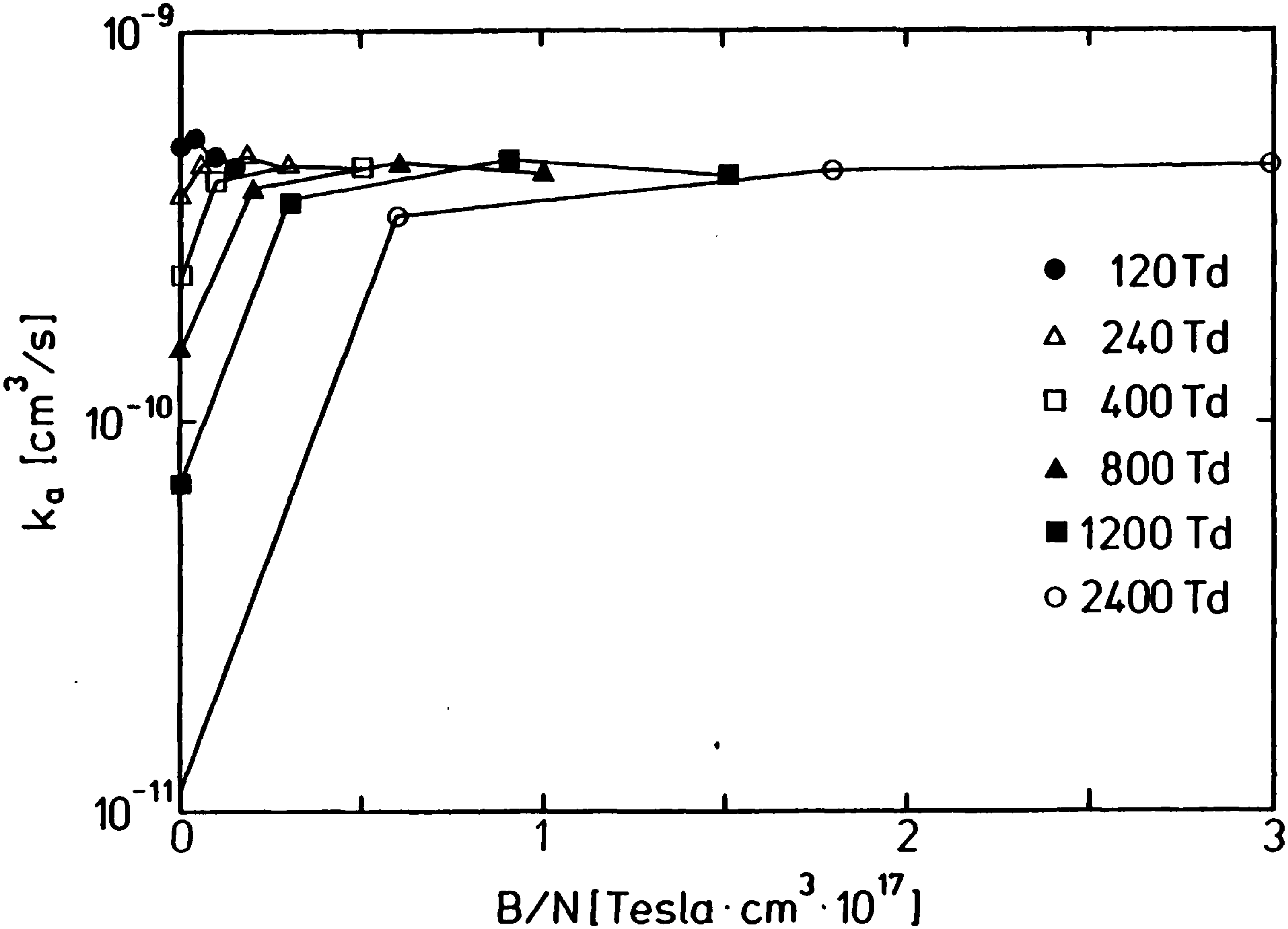

Fig. 3. Attachment rate coefficient k_i as a function of reduced magnetic flux density B/N with the reduced electric field strength E/N as a parameter in 20-percent SF_6-80-percent He.

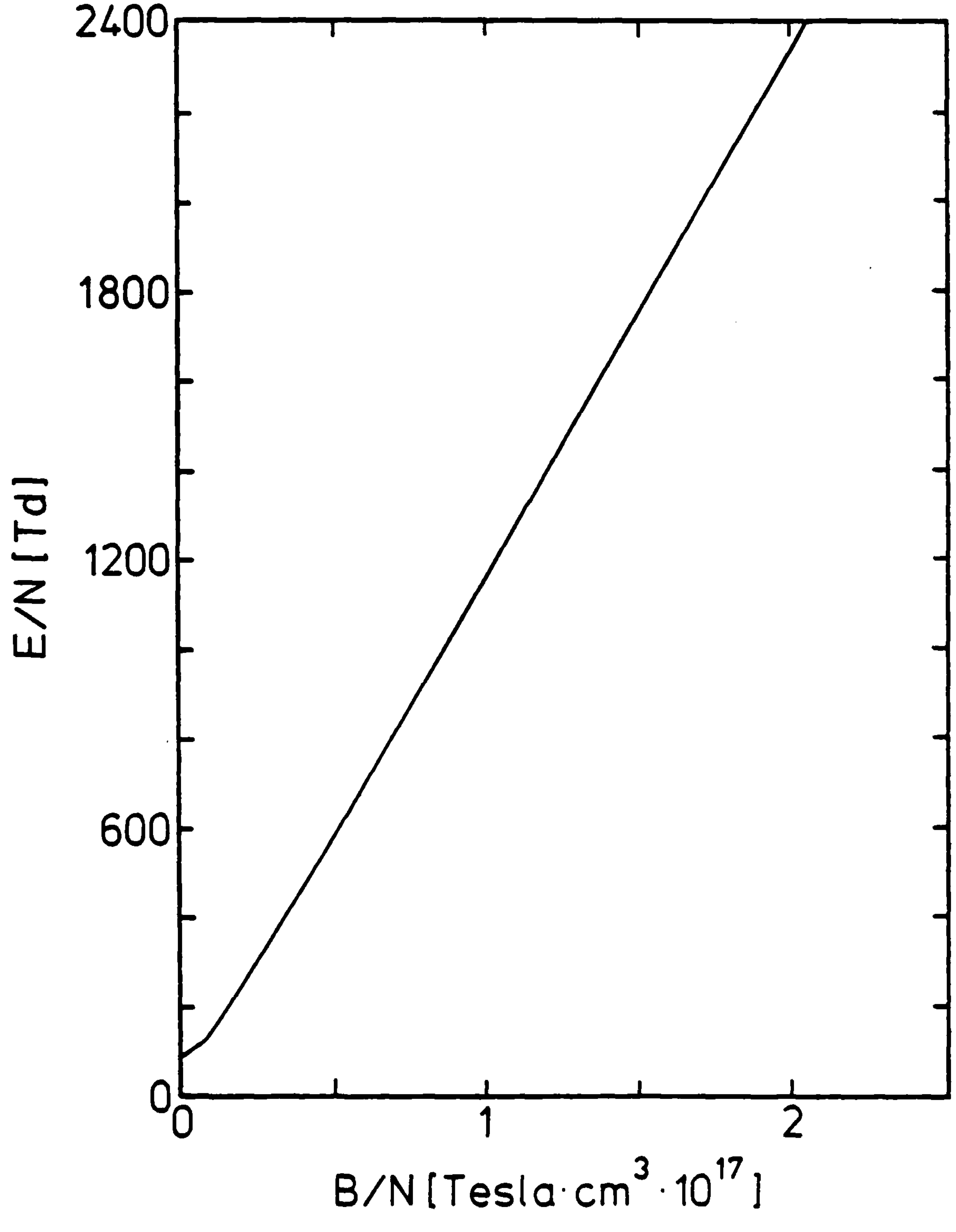

Fig. 4. Calculated positive column equilibrium reduced electric field strength E/N versus reduced magnetic flux density B/N for 20-percent SF_6-80-percent He.

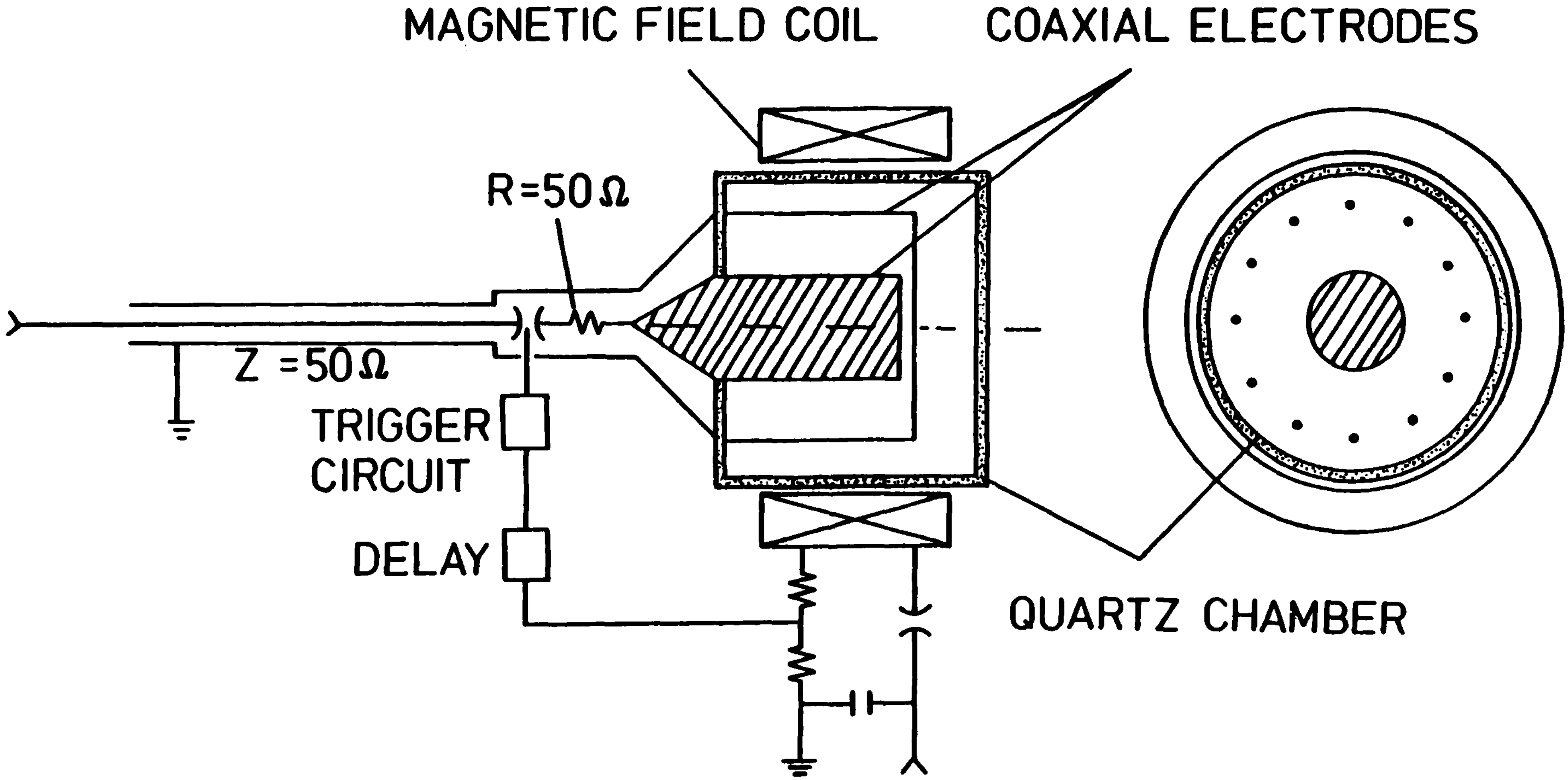

Fig. 5. Experimental apparatus.

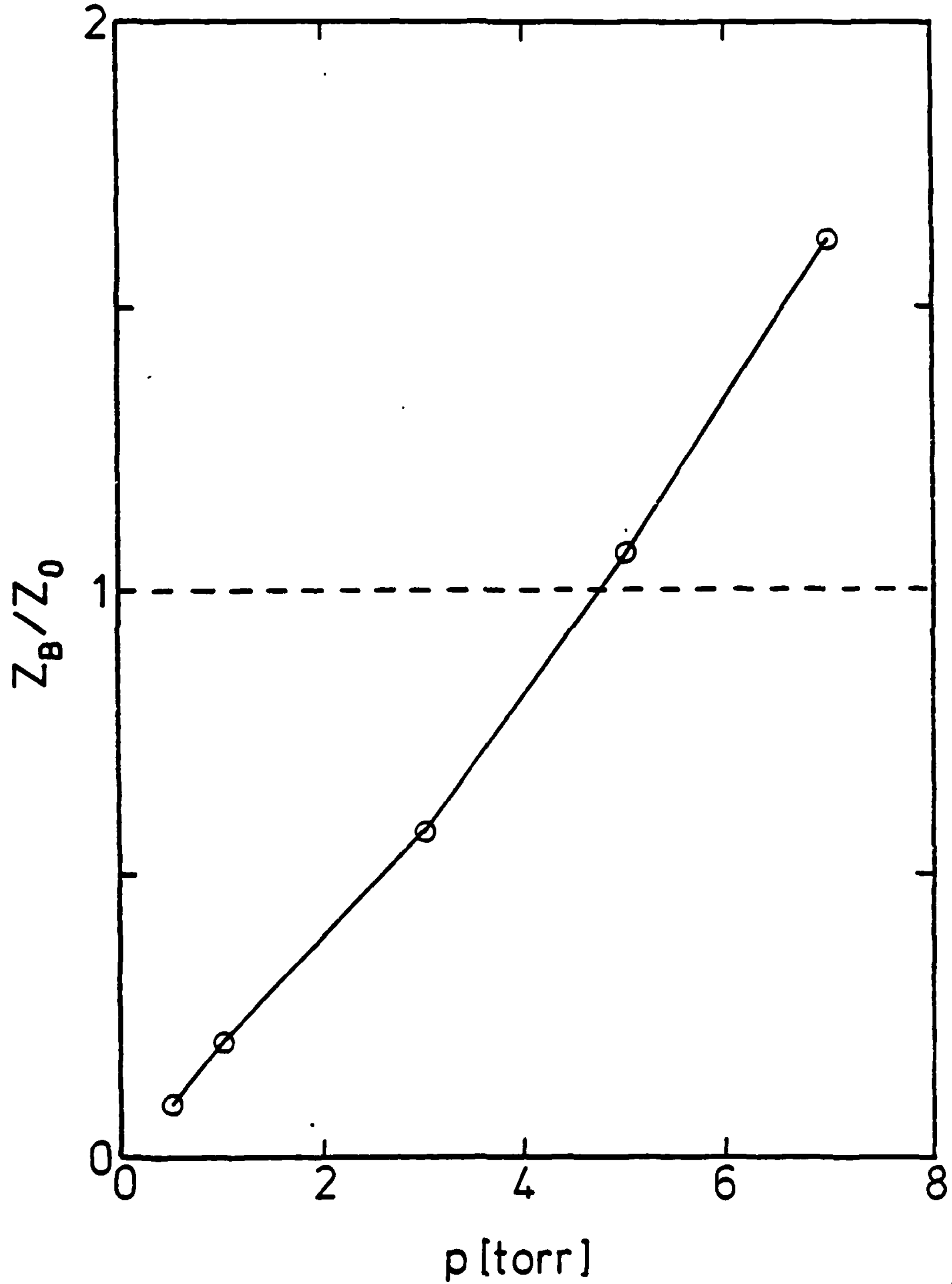

Fig. 6. Discharge impedance with magnetic field, Z_B, normalized to discharge impedance without magnetic field, Z_0, as a function of gas pressure p for 20-percent SF_6-80-percent He and B = 0.2 T. The circles are the experimental points.

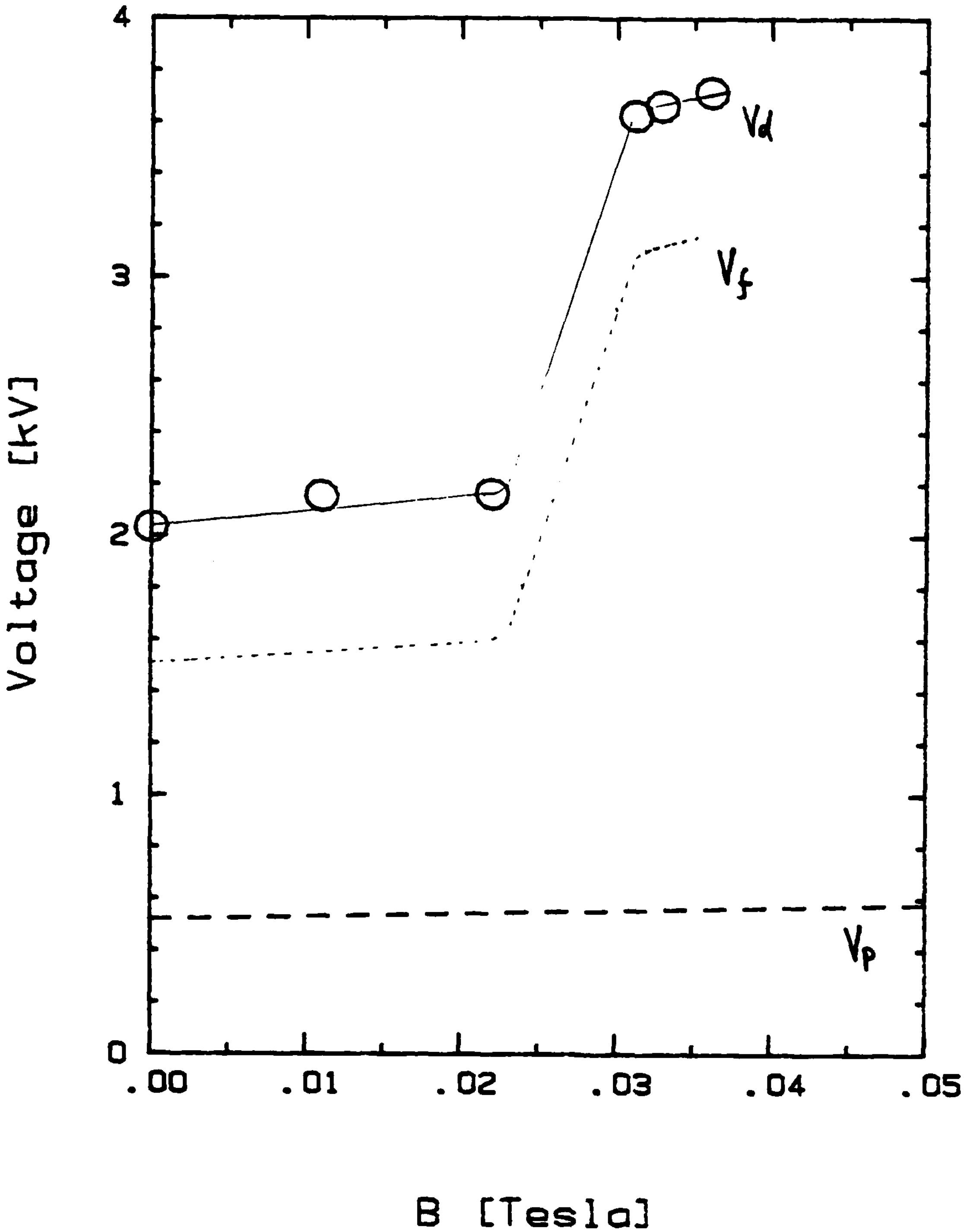

Fig. 7. Discharge voltage V_d, calculated positive column voltage V_p, and derived electrode fall voltage V_f as a function of magnetic flux density B for 20-percent SF_6-80-percent He at p = 8 torr. The circles are the experimental points.

ABSTRACTS FOR CONFERENCE PRESENTATIONS

ABSTRACT PRESENTED AT
1986 IEEE INTERNATIONAL CONFERENCE ON PLASMA SCIENCE (COPS)
SASKATOON, CANADA MAY 19-21, 1986

Magnetic Control of Low Pressure Glow Discharges*
K. H. Schoenbach, T. J. Powers, Old Dominion University, Norfolk, VA, J. R. Cooper, Texas Tech University, Lubbock, TX, and G. Schaefer, Polytechnic Institute of New York, NY, -- The application of crossed magnetic fields to a glow discharge operated on the low pd-side of the Paschen minimum, leads to a decrease in breakdown strength and resistivity of the discharge plasma. If the gas pressure is such that pd is on the high side of the Paschen minimum, the application of a crossed magnetic field has the opposite effect. In this pd-range, where the characteristic of the discharge is determined by electron-molecule collisions, rather than by electrode (γ) processes, the applied magnetic field causes a change in the rate coefficients and transport properties of the plasma, such that breakdown field strength and resistivity is increased.

It was shown by means of Monte Carlo calculations for electrons in He:SF_6 mixtures that the application of crossed magnetic fields shifts the electron energy distribution towards lower energy values. Consequently, through the change in the rate coefficients for ionization and attachment the sustaining field in the discharge plasma is increased. This magnetically induced voltage rise was studied in a coaxial glow discharge. Comparing the computationally obtained values for the voltage drop across the positive column and the measured voltages across the discharge it is apparent that processes in the cathode fall region strongly influence the characteristic of the magnetically controlled discharge. A drastic rise of the cathode fall above a value of B = 0.25 T is observed. This effect can be utilized in operating a magnetically controlled discharge as an opening switch in an inductive energy storage system.

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Gaseous Electronics

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The Influence of Transverse Magnetic Fields on the Current-Voltage Characteristics of Glow Discharges,* K.H. SCHOENBACH, S.T. KO, T.J. POWERS and V.K. LAKDAWALA, Old Dominion University, Norfolk, VA --Measurements of the steady-state current-voltage characteristics of abnormal glow discharges in transverse magnetic fields have been performed in He and He/SF_6 mixtures at a pressure of 8 Torr. The discharge voltage in He/SF_6 increases by a factor of two with applied magnetic field of less than 0.3 T. In He the discharge voltage decreases with increasing magnetic field. Monte Carlo codes were used to determine the rate and transport coefficients in the positive column and in the cathode region. With the obtained values the spatial variation of charged particle densities and the electric field between plane-parallel electrodes was calculated using a continuum model.

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Magnetic Control of Low Pressure Gas Discharges,* J.R. Cooper and K. H. Schoenbach, Old Dominion University, Norfolk, Virginia 23508 and G. Schaefer, Texas Tech University, Lubbock, Texas 79409--The positive column of a low pressure gas discharge in a transverse magnetic field was modeled using a Monte Carlo code. Due to the shift of the electron energy distribution towards lower energies the ionization coefficient is reduced when the magnetic field B is applied. In a gas mixture containing an electronegative gas with the attachment cross section peaking at values below the mean energy of the electron distribution, the magnetic field causes additionally an increase in the attachement rate coefficient. In a gas mixture of He and SF_6 (80%: 20%) at about 10 Torr, both mechanisms lead to a sharp rise of the equilibrium electric field in the positive column above a threshold value of B~0.4 T. This effect offers a means to use low pressure discharges, operated above the pd-value of the Paschen minimum, as magnetically controlled opening switches.

*Work Supported by GTE Laboratories, Inc. and the Center for Energy Research, Texas Tech University

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Submitted before funding confirmed by N00014-85-K-0602.

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