MAGNETICALLY DRIVEN INSTABILITIES IN GAS DISCHARGES

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MAGNETICALLY DRIVEN INSTABILITIES
IN GAS DISCHARGES

THESIS

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By

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CHAPTER I

INTRODUCTION

In 1940 Cummings and Tonks (3) made observations on the behavior of a low-pressure gas discharge in the presence of a longitudinal magnetic field. The electron cross-section distribution was observed to be stable with or without the presence of the magnetic field which was varied from zero to 120 gauss. No constricting effect occurred in the presence of a magnetic field. The results of this experiment appeared to be in agreement with classical theory (9).

Later, Bohm et al. (2) observed in experiments on the diffusion of ions in a magnetized arc plasma a large discrepancy between the observed diffusion of particles across the magnetic field and the corresponding predicted values. As a result of this large discrepancy Bohm postulated that the principal mechanism of diffusion was by means of plasma oscillations. Later, however, Simon (8) pointed out that plasma oscillations need not be postulated in order to explain Bohm's measurements. The electric field caused by any charge imbalance has a much greater effect on currents in the direction of the magnetic field.
lines than across the field lines due to the greater conductivity in the direction of the field. As a result, space-charge neutralization is maintained by reducing slightly the electron current from a region of positive charge to the end of the container or increasing slightly the electron current from a region of negative charge to the end of the container. Electrons and ions, as a result, need not diffuse across the magnetic field at the same rate.

Lehnert (6), in 1958, in experiments with a gas discharge positive column in the presence of an applied magnetic field observed a distinctive mode of operation when the field exceeded a certain critical value. These experiments also showed that the rate of diffusion of charged particles across the field decreases monotonically with increasing field, up to a critical value of the field beyond which the diffusion rate rapidly increases. Allen, Paulikas, and Pyle (1) have recently corroborated Lehnert's early results and added substantial detail to the description of the anomalous mode in which a helical structure is present. Values of the critical field and rotation frequency of the helical perturbation were found to be in close agreement with the theory of Kadomtsev and Nedospasov (5).

Guest and Simon (4) have extended the theory of Kadomtsev and Nedospasov to the low-pressure case in order
to explain a phenomenon observed by Neidigh and Weaver (7) which is similar in some respects to the positive-column behavior.

In the low-pressure theory (4) as contrasted with the length-dependent critical field predicted by Kadomtsev and Nedospasov (5), the critical field is independent of the discharge length, suggesting the possibility of observing an instability in a short discharge tube.

In the present experiment a gas discharge plasma generator was designed and constructed and a search was made for evidence of a plasma instability due to the influence of an externally applied magnetic field. The evidence for such an unstable mode of operation is too indirect to make possible a positive conclusion, but an approach to more certain identification will be indicated.
CHAPTER BIBLIOGRAPHY


CHAPTER II

EXPERIMENTAL DESIGN

A secondary plasma was formed around an arc discharge five centimeters long across the diameter of a cylindrical pyrex glass pipe as shown in Figure 1. The magnetic field was along the diameter of the pipe. The electron source was a heated tungsten filament 0.0508 centimeters in diameter and twenty centimeters long connected to four twelve-volt batteries in parallel arrangement. Filament currents ranged from twelve to fourteen and one-half amperes. The anode, consisting of a carbon block 2.54 centimeters square, was biased one hundred twenty-five volts positive with respect to the filament. Electrons accelerate along magnetic field lines toward the anode forming ion-electron pairs which diffuse out into the secondary plasma region. The experiment was performed using nitrogen gas at pressures ranging from four to thirty-five microns. The pumping rate was held constant during the entire experiment. Various pressures were obtained by adjusting a gas inlet valve. The discharge current ranged from one to ten milliamperes depending on the pressure and filament current.

The three filament designs that were tested are shown
in Figure 2. Design I consisted of a single coil of tungsten wire 0.0508 centimeters in diameter and twenty centimeters long wound into a coil with a 0.95 centimeter diameter. This design sagged when heated causing the contact of its adjacent turns which resulted in an abrupt rise in filament current. Design II consisted of three coils of tungsten wire 0.0254 centimeters in diameter and twenty-five centimeters long, each wound into a coil 0.476 centimeters in diameter. It was thought that Design II would provide a more uniform source of primary electrons; however, it failed for the same reason as Design I. Design III consisted of a single wire twenty centimeters long and 0.0508 centimeters in diameter insulated except for the section across the top of the inverted U-shape. This design performed satisfactorily. Emission of electrons is for the most part from the center portion of the filament because the filament insulation acts as a heat sink. Over long periods of use the filament cross-section decreases changing the resistance of the filament and thus its temperature for a fixed filament current. The useful life of a filament of this type ranges from two to five hours.

The two anode designs which were tested are shown in Figure 3. The first design was a tungsten rod 0.476 centimeters in diameter bent into an L-shape at one end. This
design heated excessively causing additional emission of new electrons and initiating a high-current discharge capable of melting the anode. The second design was a carbon block 2.54 centimeters square which provided the discharge with a uniform and relatively large surface area.

The magnetic field could be varied from zero to six kilogauss. The magnetic field was directed from the filament toward the anode during the present experiment.

The initial test run of the generator failed. The discharge became uncontrollable, melted the tungsten anode in a matter of seconds, and broke the glass pipe.

A ballast resistor was placed in the discharge circuit to control the discharge current. Later it was found that the ballast resistor was not necessary if the filament current was controlled and the carbon anode was used. Sporadic high-current breakdowns occurred when the filament current was not limited. These breakdowns appeared as sparks and bright "flash-overs" between the electrodes. It has since proved possible to eliminate these irregular current surges by completely covering the electrode supports with glass tubing. As a precautionary measure the discharge circuit was fused during the entire operation.

The operating procedure is as follows:

(1) Assemble the apparatus.

(2) Pump the system down several times; flood it each time
with gas. This procedure helps eliminate contamination in the system.

(3) Adjust the gas inlet valve to permit the system to reach the desired pressure.

(4) Connect the battery supply to the filament and the potential to the anode in order to ignite the arc discharge.

(5) Allow the discharge current to stabilize and then monitor the discharge current as a function of increasing magnetic field.
CHAPTER III

INTERPRETATION OF DATA

The experiments performed were intended to detect the existence of any disturbances in the plasma caused by an externally applied magnetic field. Discharge current was measured as a function of magnetic field at various pressures. It is estimated that the pressure can be read to within one-half a micron, the discharge current to within one-hundredth of a milliampere, and the magnetic field to within twelve gauss. Other controlled parameters of the system, i.e., filament current and anode potential, were maintained constant by using large banks of storage batteries.

The character of the arc discharge depends strongly upon the filament temperature which greatly influences the source of primary electrons. Filament temperature, however, cannot be controlled nor measured so accurately as filament current.

Figure 4 shows the relation of discharge current to the magnetic field at three pressures. Discharge current decreases more or less uniformly with increasing magnetic field up to a certain critical value of the field, then it
increases abruptly. The critical value of the field seems to depend roughly linearly upon the pressure over the restricted range of pressures examined as shown in Figure 5. The graph shows a reasonably linear dependence of critical field on pressure. Above approximately twenty microns pressure the effect becomes difficult to observe.

A possible explanation of the disappearance of the unstable mode at higher pressures is the limited plate voltage. The discharge is operating at so high a pressure that space-charge limitation of filament emission is on the verge of extinction because large electron concentrations which would at low pressure cause the high negative potential necessary to limit filament emission are neutralized by nearly equal concentrations of ions; hence, further increases in pressure provide enough additional ions to neutralize completely the negative space-charge and allow the filament emission to be limited only by its temperature. With the presence of space-charge an increased diffusion of ions from the plasma would be noticed as an increased escape in electrons, thus as a rise in discharge current since the plasma must remain electrically neutral.
CHAPTER IV

THEORY

The following conditions are assumed by the Guest and Simon Theory (1). An axially symmetric plasma is created by ionization along the axis of the arc chamber. Away from the axis there is only diffusion and streaming. Collision times are sufficiently large so that the magnetic field inhibits the motion of ions as well as electrons, i.e., $\omega_e \tau_e \gg \omega_i \tau_i \gg 1$ where $\omega_e$ and $\omega_i$ are the cyclotron frequencies of electrons and ions respectively and $\tau_e$ and $\tau_i$ are collision times of electrons and ions respectively.

Assuming the electron-neutral and ion-neutral cross-sections $\sigma_e$ and $\sigma_i = 10^{-15}$ square centimeters and the electron temperature $T_e = 10$ electron-volts and the ion temperature $T_i = 1$ electron-volt, $\omega_e \tau_e$ is found to be approximately $1.3 \times 10^3$ and $\omega_i \tau_i$ approximately 36.3 for a field of 240 gauss and a pressure of four microns.

The radial density distribution depends essentially upon the external magnetic field strength as long as the plasma remains stable. The conductivity transverse to the field is negligible compared to the conductivity along the field. The arc chamber is assumed to be a grounded
conducting cylinder, so that it acts as a perfect sink for all ions and electrons which strike it.

The present experimental geometry is essentially asymmetrical. Axial symmetry is maintained reasonably well due to the greater part of electron emission being from the center of the filament; however, the electrodes are not at all symmetrical. The radial distance displayed to the plasma is large so that one can suppose the plasma to be bounded by an infinite sink. The radial distance displayed to the plasma is at least five centimeters through a total angle of two-hundred degrees with the smallest radial distance displayed being 3.8 centimeters. Ions and electrons which do not strike the walls probably recombine.

The mean free paths of electrons and ions are large compared to the length of the cylinder, thus permitting some electrons and ions to stream to the electrodes. For example, calculation shows \( \lambda_e \equiv 100 \) centimeters and \( \lambda_i \equiv 17 \) centimeters for a pressure of four microns.

Little variation in density along the axis of the chamber is permitted due to the rapid streaming. Ionization is estimated to be about one percent, so that diffusion is a result of ion-neutral and electron-neutral collisions. Binary collisions between charged particles play a negligible role.

Direct streaming of electrons and ions to the ends of the arc chamber provides a mechanism for instability in the plasma. Electrons tend to stream longitudinally more rapidly
than ions due to their greater thermal velocity. Ambipolar electric fields develop as a result of unequal streaming and unequal diffusion which tend to reduce the difference in the two flow rates. Exact cancellation in a single direction does not occur due to the fact that ions tend to diffuse transversely out of the plasma more rapidly than do electrons. Diffusion out of the plasma is by random changes of the location of the Larmor orbit of the particle after each collision. The deflection is of the order of a Larmor radius and since the more massive particle has a larger Larmor radius it diffuses faster. This results in a net streaming of electrons through the ions in the direction of the field. Under these circumstances a helical perturbation of ions and electrons together can give rise to a charge separation as shown by Moh (2). Because of the electric field which results from the charge separation, the system may be unstable depending on whether \( \vec{E} \times \vec{B} \) points outward or inward.

The following expression gives the value of \( B_c \), the critical magnetic field, according to Guest and Simon (1).

\[
B_c = \frac{4 \pi m_i}{e \gamma_i} \left( \frac{m_i T_i}{m_e T_e} \right)^{1/2} \frac{1}{1 + T_e/T_i}
\]

where \( m_i \) and \( m_e \) are the ion mass and electron mass respectively and \( e \) is the electron charge. If one assumes the same values as stated earlier for \( \gamma_i \), \( T_i \) and \( T_e \) and a pressure of four microns calculation yields a value of \( B_c \equiv 270 \) gauss.
CHAPTER BIBLIOGRAPHY


CHAPTER V

CONCLUSION

The data give clear evidence of an abrupt change in the discharge characteristics when the magnetic field is increased above a critical value which appears to vary linearly with the ambient pressure.

It is tempting to propose that this abrupt change in discharge current is associated with the onset of "enhanced diffusion" (4) which in turn may possibly be connected with an instability in the secondary plasma of the type predicted by Simon and Guest (3). This connection is suggested by the Langmuir analysis (5) which shows that the arc current would be limited by space charge considerations provided the applied potential is not so high as to draw all the current emitted by the hot cathode. That this saturation is not the case was observed experimentally by determining the volt-ampere characteristics of the discharge as well as by observing the plate current-filament temperature characteristics.

A measure of the diffusion rate in the radial direction would directly connect the results of this experiment with the notion of enhanced diffusion. Such an experiment
could take the form of inserting probes into the secondary plasma and measuring this diffusion rate. Similarly one could look for an increase in radio frequency noise corresponding to the onset of unstable plasma oscillations as was done by Allen, Paulikas, and Pyle (1).
CHAPTER BIBLIOGRAPHY


Fig. 2--Diagram of filament designs

Design I

Design II

Design III
Fig. 3--Diagram of anode designs

Design I

Design II
Fig. 4—Arc current versus magnetic field
Fig. 5--Critical field versus pressure
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