Study of r.f. break down characteristics of argon at high pressure in presence of magnetic field

Vidy A Ram and D. C. Sarkar*

Department of Physics, Aligarh Muslim University, Aligarh

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The r.f. (16 mc/s) break down characteristics of argon have been studied, in the presence of a low intensity (0-180 gauss), longitudinal and a high intensity (100-1500 gauss), non-resonant transverse magnetic field over the pressure range of 0-5-100 mm Hg. In the case of a longitudinal magnetic field, break down potential increases monotonously with increasing magnetic field. But in the case of transverse magnetic field it shows a significant increase up to a certain field and then decreases slightly with the increase of field at pressures above 40 mm Hg.

INTRODUCTION

In recent researches particular attention has been devoted to the r.f. plasmoids; the mechanism of such an r.f. discharge was explained by Taillet & Brunet (1965) and Allis (1956) on the basis of plasma parallel model. The ordinary r.f. discharge with no magnetic field is, therefore, a rather well understood phenomenon, while the r.f. discharge excited in the presence of a magnetic field has not yet been completely studied and explained.

The r.f. break down characteristics of various gases were first studied by Townsend & Gill (1938), and they concluded that a magnetic field reduces the coefficient of diffusion in the direction perpendicular to it. They also concluded theoretically that at pressures greater than 0-14 mm, the electric force required to start the discharge, in the absence of magnetic field, was slightly less than that required in its presence. This is due to the fact that the mean increase in the energy ($E_{hf}$) of an electron in presence of magnetic field:

$$E_{hf} = ma^2T^3\left[1 + 1/(1 + 4q^2T^2)\right]/4,$$

and the mean increase in the energy of an electron ($E_T$) when there is no magnetic field:

$$E_T = ma^2T^3/2(1 + q^2T^2)$$

where $q$ = angular frequency, $a$ = acceleration = $Xe/m$ and $X$ = electric field.

* Present address—Department of Applied Physics, Z. H. College of Engineering and Technology, Aligarh Muslim University, Aligarh.
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Since at low pressure $qT$ is greater than $\frac{1}{2}$, the mean energy $E_{HT}$, acquired by the electron in the magnetic field intensity $H = \frac{mg}{e}$ is greater than the energy $E_T$ acquired under the action of the same electric force, when there is no magnetic force. At high pressure, where $qT$ is less than $\frac{1}{2}$, the energy $E_{HT}$ is less than $E_T$.

Several other workers including (Lax, Allis & Brown 1950 Ferrite & Veronesi 1955, Bacri 1965 and Agnello et al 1966), solved this problem to a great extent. However, almost all of these studies were done in the low pressure range and they concluded that the break down voltage was a function of pressure, frequency of excitation voltage and the geometry of the gas container. They observed two minima at lower frequencies and one at higher frequencies in the pressure range of a few microns to 0.14 mm Hg. The lowering of break down potential near resonant conditions was observed theoretically as well as experimentally and can be predicted both by the Typical Electron Theory and Boltzmann Theory.

The break down characteristics of gases at high pressure using high frequency exciting electric field in presence of low intensity longitudinal and high intensity nonresonant transverse magnetic fields, have not been investigated so far experimentally.

The experiment reported in this paper has been performed in order to study the break down characteristics of rf discharge at pressure of 0.5-100 mm Hg and in presence of low intensity longitudinal and high intensity, non-resonant, transverse magnetic fields. This paper gives experimental support to the theoretical prediction of Townsend & Gill (1938) namely, that in the pressure range above 0.14 mm Hg, the electrical field required to start the discharge in the absence of magnetic field is slightly less than that in its presence.

**Experimental Arrangement and Technique**

The block diagram of the apparatus used for these measurements is depicted in figure 1. The discharge was produced by applying an rf exciting voltage (15 mc/s) through two copper rings mounted on a discharge tube (4 cm diameter, 25 cm length) made of pyrex glass. The rf field intensity was increased slowly by increasing dc plate voltage of rf oscillator from zero till the break-down of the gas obtained. The rf voltage required to start discharge was noted from the calibration curve between the dc plate voltage and rf voltage. Copper rings (electrodes) were placed at a distance equal to 2/3 of their radius so that a sufficiently uniform field was achieved (Gill & Engel 1948).

The negative resistance type push pull rf oscillator (Sarkar 1970) having 304T/L power triode tubes have been used. The output power of the oscillator
is quite stable about 500 watts. The oscillator can be tuned to any desired frequency from 10 to 30 mc/s. In the present investigation the oscillator was tuned to the frequency 16 mc/s.

A continuously variable magnetic field was produced along the axis of the discharge tube by a solenoid (10 cm diameter, 40 cm length). The break-down voltage of argon was measured for different intensities of magnetic field, varying the magnitude of the current passed in the solenoid at various pressures, ranging from 0-5 to 100 mm Hg by a technique similar to that of Gill & Engel (1948).

The glass tube was placed in between the two pole pieces of an electromagnet in such a way that the magnetic field was transverse to the applied exciting electric field. The high intensity nonresonant magnetic field was produced by passing current through the coils of the electromagnet. Break-down voltage was measured at different pressures and magnetic field intensities.

RESULTS AND DISCUSSIONS

The break down potential of argon has been measured at different pressures inside the plasma tube for different intensities of longitudinal, as well as transverse magnetic field. The results of the measurement are shown graphically.

The behaviour of the break down potential of argon in presence of low intensity magnetic field are depicted in figure 2. Here rf break down potential have been plotted against the magnetic field intensity. The rf voltage was measured from the BARC electronic multimeter model EM 750. We observed in this case that at all pressures the break down potential increases regu-
larly with the increase of magnetic field intensity. But the gradient (rate of increase) of break down potential decreases slowly as the intensity is increased. These results are in good agreement with the theoretical prediction of Townsend and Gill (1938).

![Figure 2](image)

Figure 2. Variation of breakdown potential with longitudinal magnetic field at different pressures.

![Figure 3](image)

Figure 3. Variation of breakdown potential with transverse magnetic field at different pressures.

The characteristics of break-down potential in presence of high intensity non-resonant transverse magnetic field are shown in figure 3. Here we observed that break down potential increases regularly with the increase of magnetic field intensity up to the pressure 40 mm Hg. But the behaviour of the break down potential above this pressure is rather anomalous. At the pressure greater than 40 mm Hg, it has been observed that the break down potential increases significantly to its maximum value and then decreases slightly with the increase of magnetic field intensity. This behaviour of the break down field particularly
at this pressure range is still to be studied in more details and to be explained clearly. This behaviour may be attributed to the self excitation of some low frequency standing waves inside the plasma as studied by Ishii (1968), Enjoji et al (1968) and Galiev et al (1964).

In figure 4 the variation of break down potential with pressure has been represented. Here we find that for all intensities of magnetic field break down potential increases as we increase the pressure inside the plasma tube.

![Figure 4. Variation of breakdown potential with pressure at 100 gauss longitudinal and 200 gauss transverse magnetic field.](image)

The experimental measurements of break down potential reported in this paper have got a particular importance due to the fact that this type of measurement in these experimental conditions have been performed for the first time, although the theoretical prediction of Townsend and Gill indicated it long back.

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Rf Conductivity of Plasma in the Presence of Magnetic Field by Frequency Shift Measurements

VIDYA RAM, AVINASH CHANDRA & D. C. SARKAR

Department of Physics, Aligarh Muslim University, Aligarh

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An attempt has been made to apply the frequency shift measurement method for the study of the variation of the rf conductivity of a plasma with pressure in the range 1-300 µHg. It is assumed that the plasma tube is a leaky capacitor, and the frequency of the rf oscillator exciting the plasma is measured with and without plasma in the discharge tube in the presence of perpendicular non-resonant high intensity (100-1500 G) and parallel low intensity (0-180 G) magnetic fields. It has been observed that the conductivity increases appreciably with magnetic field in the case of a parallel magnetic field, while in the case of a high intensity perpendicular magnetic field, the rf conductivity increases only slightly.

1. Introduction

The use of an rf signal as a probe in the study of electrical discharge phenomena was suggested by Van der Pol1. The conductivity of ionized air was measured by Childs2 at the frequency of 1 MHz by substituting a resistance of known value for the leakage resistance of the ionized air. Appleton and Chapman3 measured the variation of rf conductivity of ionized air with pressure at a frequency of the order of 1000 MHz, using a Lecher wire system coupled to a condenser within which the discharge tube was placed, and observed that the conductivity attains a maximum value at a certain pressure and then decreases. Sen and Ghosh4 have described a method for measuring the rf conductivity and explored the possibility of calculating the plasma parameters from such a measurement. Sen and Gupta5 have further investigated the rf conductivity of ionized gases such as helium, neon and argon in the pressure range of 1-700 µHg in the presence of a magnetic field (0-550 G). It has been shown by Gupta and Mandal6 also that the rf conductivity is dependent upon the external magnetic field.

2. Principle of rf Conductivity Measurement

The plasma which is excited by an rf voltage between two plates forms a condenser with varying dielectric medium. The capacity of this condenser changes as plasma becomes thicker and thicker. Now the tank circuit of the rf generator can be considered to be represented by an L-C-R circuit which has a specific resonant frequency depending upon the circuit elements, and it will vary with the change in plasma capacitance. Thus this frequency shift will give us information about the plasma capacitance from which the rf conductivity of a plasma may be calculated. This method of calculating the rf conductivity was indicated by Blackman7 and John8. Thus the frequency of the rf oscillator is measured without and with the plasma in the discharge tube, and the rf conductivity and electron density are determined.

3. Theory of the Measurements of rf Conductivity and Electron Density

As the experimental procedure followed in the present investigation is different from the usual methods, it is necessary to deduce the expression for conductivity.

The various parameters of the circuit may be defined as follows:

- L = inductance of tank circuit coil
- C = the main circuit capacitance
- C = capacitance of plasma capacitor (without discharge)
- R = discharge resistance in the tube
- f = the frequency of the oscillator when no plasma capacitor is connected
- f = the frequency with plasma capacitor present
- f = the frequency when discharge in the plasma capacitor is present

The frequencies f, f and f can be written in terms of different circuit elements, as was done by Seely9, as

\[
\omega_1 = \left(2\pi f_1\right)^2 = \frac{1}{LC_T} \quad \text{(1)}
\]

\[
\omega_2 = \left(2\pi f_2\right)^2 = \frac{1}{LC_T + C_P} \quad \text{(2)}
\]

\[
\omega_3 = \left(2\pi f_3\right)^2 = \frac{1}{LC_T + \epsilon C_P} = \frac{1}{4R^2(C_T + \epsilon C_P)^2} \quad \text{(3)}
\]

Since dielectric constant \(\epsilon\) is assumed to be unity

\[
\omega_4 = \frac{1}{LC_T + C_P} = \frac{1}{4R^2(C_T + C_P)^2} \quad \text{(4)}
\]

If A be the area of plasma capacitor plates and \(d\) the distance between the plates, the capacitance \(C_P\) and the resistance \(R\) can be written as

\[
C_P = \frac{A}{4\pi d} \quad \text{(5)}
\]

\[
R = \frac{d}{2\pi A} \quad \text{(6)}
\]

\(\sigma\) = conductivity of plasma for the frequency \(\omega_4\),

\(N\) = electron density, \(v\) = electron-molecule collision frequency.

*Present address: Department of Applied Physics, Z.H. College of Engineering & Technology, Aligarh Muslim University, Aligarh.
Substitution (5) and (6) in (4) and with the help of (1) and (2) conductivity ($\sigma$) comes out to be:

$$\sigma = \frac{1}{2} \left[ 2\left( f_2 - f_0 \right) \right]$$

$$\frac{1}{f_2^2 - f_0^2}$$

...(7)

The conductivity is much more effective in changing the oscillator frequency than the dielectric permittivity due to very large value of collision frequency; that is why dielectric constant is put very nearly equal to 1.

Using the Chapman-Appleton model of the plasma, the conductivity can be obtained from the following relation:

$$\sigma = \frac{Ne^2}{m(\gamma^2 + \omega^2)}$$

...(8)

The maximum value of the conductivity occurs at the same pressure for different values of exciting fields and the maximum value itself increases with increasing exciting field. The maximum value for conductivity is obtained by putting $v \approx \omega$ which gives the relation

$$\sigma_{\text{max}} = \frac{Ne^2}{2mo}$$

...(9)

From this relation the value of $N$ (electron density) can be calculated. The electron-molecule collision frequency can be calculated from the relation

$$v = \omega \left[ \frac{\sigma_{\text{max}}}{\sigma} \pm \sqrt{\left( \frac{\sigma_{\text{max}}}{\sigma} \right)^2 - 1} \right]$$

...(10)

4. Experimental Details

A pyrex glass tube (length 25 cm, diam. 4 cm) was evacuated to a low pressure (1-300 $\mu$ Hg) and the pressure inside the tube was measured with a Mcleod gauge. The tube was put inside the solenoid which produced a magnetic field which can be varied from 0 to 180 G depending upon the magnitude of current passed. The magnetic field due to the solenoid is thus parallel to the applied electric field exciting the plasma.

The high intensity magnetic field was produced by an electromagnet. The field varied from 100 to 15000 G. The plasma tube was placed in between two poles of the magnet such that the magnetic field is perpendicular to the exciting electric field.

The plasma was excited by means of a negative resistance push-pull type rf oscillator having a variable frequency (10-30 MHz) and power output of about 500 W, as shown in Fig. 1.

Accurate frequency measurement is the main requirement of this experiment. General Radio type 620 A, heterodyne frequency meter with crystal calibrator is used to measure the frequency. To guard against the error due to the dependence of $f_1$ upon the dc plate voltage of the oscillator, the frequency $f_1$ was measured at a number of plate voltages within the range and it was made sure that $f_1$ is independent of dc plate voltage; frequencies $f_2$ and $f_3$ were measured repeatedly and reproducible results were obtained.

5. Results and Discussion

Results of the measurement of rf conductivity and electron density are shown graphically. Fig. 2 represents the variation of rf conductivity electron density with the exciting rf voltages. As expected, the conductivity increases gradually with the increase of exciting rf voltage (curve 1), which results in lowering the frequency $f_r$. The values of electron density at different exciting fields have been calculated (at the pressure 40 $\mu$ Hg, where conductivity is maximum). These values are also shown plotted in Fig. 1. It is observed that the electron density increases rapidly at first and then gets saturated at higher fields (curve 2, Fig. 2). Fig. 3 shows the variation of conductivity with pressure at two different exciting voltages. The conductivity first increases rapidly and then decreases slowly as the pressure is increased. The variation of conductivity is of the same nature as obtained by Sen and Gupta. The conductivity is found to be maximum at the pressure between 40 and 55 $\mu$ Hg.

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Fig. 1 — Oscillator circuit with plasma capacitor

Fig. 2 — Variation of electron density and rf conductivity with rf exciting voltage

Fig. 3 — Variation of rf conductivity with pressure
Fig. 4—Variation of rf conductivity with transverse magnetic field

Fig. 4 shows the variation of conductivity with transverse high intensity magnetic field for different exciting rf fields. It is observed that the conductivity with magnetic field, at low exciting rf voltages increases markedly while at high exciting rf voltages it changes only slightly at all pressures. A similar behaviour is also observed by Sen and Gupta\(^5\) and Gupta and Mandal\(^6\). The maxima in the conductivity, however, cannot be expected as the electron cyclotron frequency \(\left(\frac{eB}{m}\right)\) is much higher than the plasma exciting frequency, which is about 30 MHz.

It is seen from Fig. 5 that the variation of conductivity in parallel, low intensity magnetic field shows a slight increase with increasing magnetic field at all exciting rf voltages. As reported by Kumar et al.\(^5\), in the case of a parallel magnetic field, the breakdown voltage decreases with increase in magnetic field. The conductivity which is proportional to the inverse of breakdown voltage should increase also.

The behaviour of the rf conductivity for air observed in this study is comparable to that reported by others\(^4,5\). The other plasma parameters (such as electron density, electron temperature and collision frequency) can be computed by the method employed in the present investigation.

This technique provides an accurate method for determining the rf conductivity and, hence, other plasma parameters, because of the fact that the plasma is free from all kinds of disturbances such as insertion of probe, etc., inside the plasma, and from any kind of interaction of outside waves with the plasma. The important essential prerequisite in the method is to note the frequency shift accurately. The results thus obtained are expected to be more exact than those obtained by other methods.

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