CHARACTERISTICS OF GAS DISCHARGE PLASMA IN MAGNETIC FIELD

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ABSTRACT

The behavior of gas discharge plasma may be affected, in various manners, by the configuration of the magnetic field. In this paper, we are concerned with its characteristics in longitudinal magnetic field: In uniform field, an appearance of contracted column is characteristic, while in non-uniform field an anomalous plasma distribution in the direction of the magnetic field is distinctive.

I. Introduction

So far the effects of magnetic field on gas discharge plasma have been studied only as to how the Schottky's theory of positive column should be modified in longitudinal magnetic field. Such investigations were carried out by many peoples experimentally and theoretically.[1)~7)] In general, the longitudinal magnetic field has a function to depress the radial diffusion of charged particles in positive column. As a result, the radial density distribution is steepened, in other words, the column is contracted.

In this paper, we deal with anomalous phenomena appearing in uniform and non-uniform longitudinal magnetic field. Of uniform magnetic field, we are concerned with the contraction phenomena in a discharge tube, in which no positive column exists when the magnetic field is absent. A non-uniformity of density appears as a result of the non-uniformity of the field.

II. The contracted Column in uniform longitudinal magnetic Field

Many investigations of the contraction phenomena in longitudinal magnetic field have been made under the condition that positive column existed. Now we give attention to the contraction phenomena in a discharge tube having no positive column.

With such a purpose, we prepare a discharge tube as shown in Fig. 1, in which Ar is filled with the pressure of 0.1 mm Hg. The magnetic field is applied parallel to the direction of the discharge axis, as shown in Fig. 1. The strength of the field does not exceed 1,500 gauses.

When the magnetic field is not applied, a

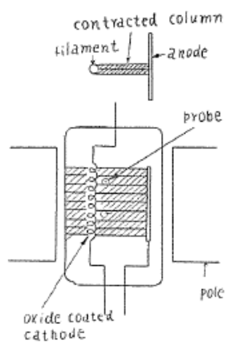

FIG. 1. Discharge tube.

luminous glow appears in the front of the cathode (oxide coated) and the rest of the space between the anode and the cathode is covered with a feeble luminosity.

1. The Characteristics of Discharge and the contracted Column

As the magnetic field is increased, the appearance of the space between anode and cathode changes. When the strength of the magnetic field is in excess of several tens gauses, a luminous contracted column appears in the feebly luminous region. The contracted column has a shape of straight stripe with the thickness nearly equal to the diameter of the spiral of the cathode and the width equal to the length of the cathode, as shown in Fig. 1. The contracted column has many cores in it. The core starts from the point on the cathode which is nearest to the anode.

The voltage of the discharge tube is lowered initially, with intensifying the magnetic field, as shown in Fig. 2. However, further increase of the magnetic field does not introduce any change in the tube voltage. The decrease of the tube voltage observed in weak field can be explained that the diffusion of charged particles across the magnetic field is depressed by the magnetic field.

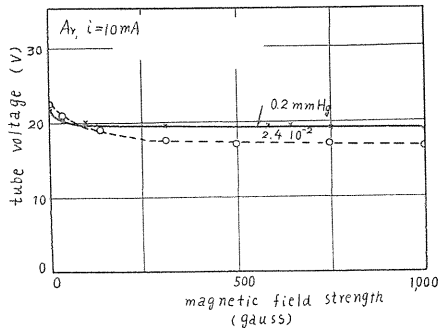

FIG. 2. Plots of tube voltage vs. magnetic field strength.

2. The Probe Characteristics and the contracted Column

Now we examine what happens in the contracted column by means of the single probe method. Two cylindrical probes made of Mo, one being parallel to the line of force and other perpendicular to it, are used for such purpose.

Fig. 3 shows typical characteristics obtained by the former probe (the transverse probe), while Fig. 4 those obtained by the latter probe (the parallel probe), both taking the magnetic field strength as a parameter. The transverse probe is placed at a point distant 1 cm from the discharge axis, and the parallel probe is placed on the axis.

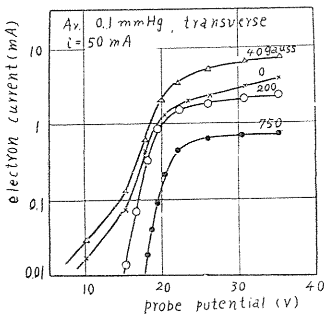

FIG. 3. Probe characteristics, taking the field strength as a parameter (transverse probe).

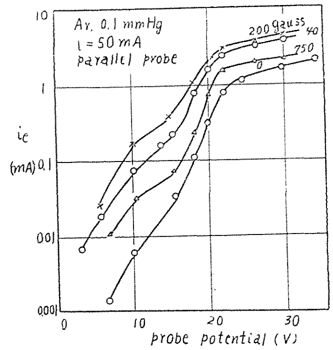

FIG. 4. Probe characteristics, taking the field strength as a parameter (parallel probe).

From Fig. 3, it is seen that, the increase of magnetic field results in an increase of slope of the part, by which the mean energy of electron can be estimated. This fact indicates the decrease of the number of fast electron. Since the probe is outside the contracted column, this fact means that the groupe of the fast electron is confined into the contracted column. On the contrary, the probe characteristics shown in Fig. 4 indicates that the number of the fast electron increases with increasing magnetic field. This result confirms also the existence of the fast electron in the contracted column, because in this case the probe is inside the contracted column.

Such fast electrons may be either the primary electrons emitted from the hot cathode or the electrons undergone a slight scattering befor it reached the probe, which was apart 0.6 cm from the cathode. The energy of the fast electron is measured to be several eV. From the above experiments, it was found that the fast electron with energy of several eV can be trapped into the contracted column.

Next, the characteristics of the contracted column are examined by measuring the plasma density. In order to obtain a knowledge of the plasma density, the ion density deduced from an ion current flowing into a negative probe must be used, because the ion collection on the probe can be hardly affected by the magnetic field used in our experiments, in which the gyrating radius of ion is sufficiently large compared with the thickness of the ion sheath. However, the electron collection is so greatly influenced by the magnetic field that it can not be employed to estimate the plasma density. The electron collection is generally depressed by virtue of the decrease of diffusion across the magnetic field. It was seen that the diffusion coefficient across the magnetic field is reversely proportional to the square of the field strength, unless any hash does not generate in the plasma. The depression of diffusion across the magnetic field due to the hash is an important process, with which we are concerned in detail.

Fig. 5 illustrates the relation between the ion current flowing into the probe held at an appropriate negative potential and the magnetic field strength. As

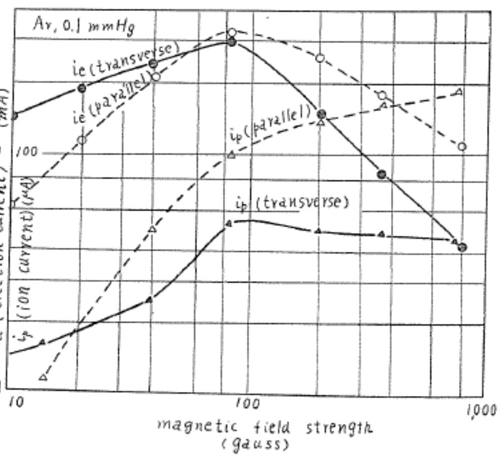

FIG. 5. Currents of electron and ion as a function of the field strength.

shown in Fig. 5, the ion current as a mesure of the plasma density increases with increasing the magnetic field. It is an indication of the fact that the plasma density in the contracted column is very high. The reason why a maximum in the plot of the ion current vs. the magnetic field strength appears in the use of the transverse probe is that the contracted column removes from the probe in such a strong magnetic field.

Furthermore, as an evidence that the electron collection may be affected by magnetic field, plots of the electron current flowing into the probe held at the space potential against the magnetic field strength are shown in Fig. 5. In both cases using the transverse and the parallel probes, rapid decreases of the electron collection with increasing magnetic field are observed, in spite of increasing of plasma density due to the development of the contracted column. This problem will be discussed in detail in another paper.

III. Positive Column in non-uniform magnetic Field

When a solenoid with small length is used to produce a longitudinal magnetic field, an non-uniformity of the field strength may exist along the solenoid axis. The magnetic field possesses its maximum at the centre of the solenoid.

Since perfectly uniform magnetic field is not easily attained in the use of solenoid in laboratory work, it is necessary and interesting to understand how the non-uniformity affects discharge plasma such as positive column.

Next, we investigate the effect of the non-uniformity of magnetic field in connection with the discharge characteristics.

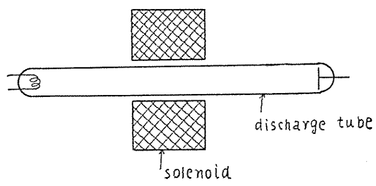

FIG. 6. Discharge tube and solenoid.

Experiments are carried out by using a cylindrical discharge tube with the diameter of 2 cm and the length of 30 cm, and a solenoid with the mean diameter of 6 cm and the length of 4 cm (Fig. 6).

1. *Discharge Characteristics*

The plots of the tube voltage vs. the solenoid current are given in Fig. 7, taking the pressure of Ar and the discharge current as the parameters. As the pressure is lowered, the increase of the tube voltage with increasing magnetic field becomes large. Such increase of the tube voltage could not be observed in the case of uniform magnetic field (see Fig. 1).

Therefore, we may conclude that the non-uniformity of longitudinal magnetic field causes the increase of the tube voltage.

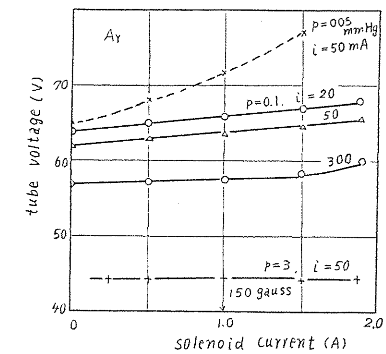

FIG. 7. Plots of tube voltage vs. solenoid current.

2. Density Distribution along Discharge Axis

Locating a cylindrical probe at the centre of the solenoid where the magnetic field is strongest, and measuring the ion current flowing into the probe held at an appropriate potential, which is negative to the surrounding plasma, as a measure of the plasma density, we obtain the results as shown in Fig. 8. When the discharge current is small, the plasma density at the centre slightly increases with increasing magnetic field strength. However, when the discharge current is large, there decreases the plasma density at the centre decreases until a minimum is reached, as the magnetic field is strengthened. The minimum value is smaller than the value when the magnetic field is absent. Such lowering of density can not be observed in the edges of the solenoid. It is also found that the lowering of the density does not appear if the pressure is raised to about several mm Hg.

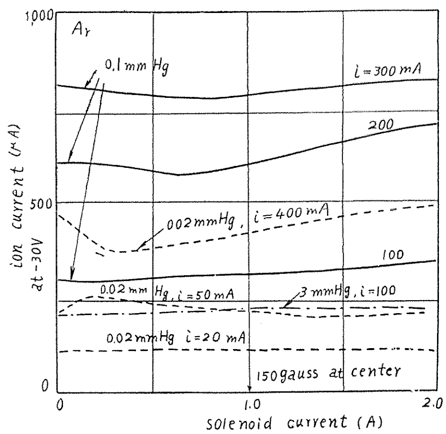

FIG. 8. Ion current flowing into a probe located at the center of the solenoid and the solenoid current.

In attempt to observe such anomality of plasma density due to the non-uniformity, we prepare a movable probe and measure the density distribution along the discharge axis. Under such a condition that the lowering of density above mentioned is observed, a minimum of density appears in the central part. Fig. 9 shows the typical example of the density distribution along the tube axis. When the discharge current is small, the minimum does not appear, but only the maximum is observed. Thus, it seems that the occurance of the minimum is characteristic when the discharge current is large.

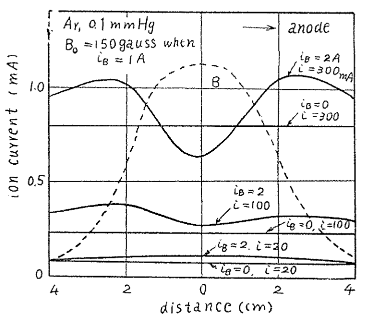

FIG. 9. Anomalous density distribution along the tube axis.

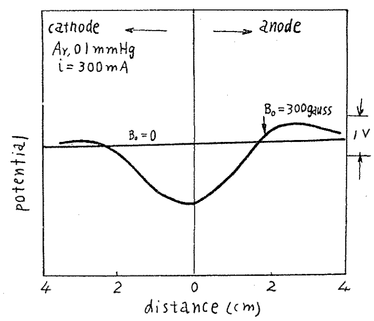

FIG. 10. Potential distribution along the tube axis.

In addition to the anomalous distribution of density along the discharge axis, a similar anomality is also observed in the potential distribution. A typical result is shown in Fig. 10. These results about the density and potential distribution indicate that the anomalous distribution of density is accompanied with that of the potential.

A further test is done to clarify how the reversal of direction of the magnetic field affects the result. From such test it is found that the anomality is produced regardless of the direction of the longitudinal magnetic field.

The above experimental results are summarized as follows;

(1) The anomality is observed when the gas pressure is sufficiently low, in other words, when the collision between electron and neutral particle can be neglected.

(2) The anomality is observed when the discharge current is large. In this case, the electric field strength or the resistivity of positive column is usually small compared with that in a case where the discharge current is small. This means that the electric field or the resistivity of positive column does not produce any appreciable effect on the anomality.

3. Theoretical Consideration of the Anomality of Density Distribution

In this section, we consider the anomalous density or potential distribution in this section theoretically. We may assume that only the magnetic effect on electron is effective and the effect of gravitational force is neglected.

In the assumption, we may describe the following expression which is valid in steady condition.[8]

$$\mathbf{E}+\mathbf{v}\times\mathbf{B}-\frac{kT_e}{e}\nabla n=\eta\mathbf{j} \tag{1}$$

where $\mathbf{E}$ is electric field, $\mathbf{v}$ velocity, $\mathbf{B}$ magnetic flux density, k Boltzmann constant, e electron charge, T_e electron temperature, n plasma density, η resistivity of plasma and $\mathbf{j}$ current density.

As mentioned above, when the discharge current is large the resistivity is small, so we may neglect the right hand side. Then we may write

$$\mathbf{E}+\mathbf{v}\times\mathbf{B}-\frac{kT_e}{e}\nabla n=0. \tag{2}$$

Now, as a axial component of magnetic term of the left hand side of Eq. (2) we may consider $v_\perp \times B_r$, where $v_\perp$ is the velocity component perpendicular to the magnetic field and B_r the radial component of the magnetic flux density which is originated from the non-uniformity of the longitudinal magnetic field.

According to Alfven's analysis,[9] the magnetic term can be expressed in terms of the gradient of the longitudinal magnetic flux density dB/dz and the magnetic moment μ as follows:

$$e(v_\perp B_r)=\mu(dB/dz). \tag{3}$$

If it is assumed that the electron collision frequency is negligibly small compared with the electron cyclotron frequency, we may write

$$\mu=(kT_e+kT_p)/B \tag{4}$$

where T_p is ion temperature. If we take the gradient in the axial direction as ∇n, and assume that $kT_e \gg kT_p$, the following equation is obtained from Eqs. (2), (3) and (4).

$$eE+(kT_e/B)(dB/dz)=(kT_e/n)(dn/dz). \tag{5}$$

Integrating Eq. (5) over z, we find the density at z as follows:

$$n=n_0 \exp\{(eV/kT_e)-\ln(B_0/B)\} \tag{6}$$

taking zero at $z=0$. Subscript 0 in the above equation indicates the value at the center of the solenoid ($z=0$).

To examine the validity of Eq. (6) numerically, we take the result shown in Figs. 9 and 10 as an example. In that case, since $B_0/B=3.3$ and $V=2.6\ V$ (at 300 gauss) at $z=2.5$ cm and $kT_e/e=1.6$, we find from Eq. (6) that $n=1.5\ n_0$, showing agreement between the computed and the observed values.

As a result, we may conclude that the appearance of the anomality observed at low pressure and large current density can be explained by the magnetic acceleration outward from the center of the solenoid, which comes from the non-uniformity of longitudinal magnetic field.

IV. Conclusion

In this paper, we investigated two magnetic effects. One is the possibility of trapping of fast electron in the contracted column, which is formed in low voltage arc discharge tube by virtue of longitudinal magnetic field. The other is the anomalous plasma distribution along the discharge axis, which is caused by the non-uniformity of longitudinal magnetic field.

This effect may introduce a serious deformation of plasma in practical use. For example, an enormous escaping of charged particles from the center of a magnetic bottle with non-uniformity of longitudinal magnetic field, may become an impendiment for hot plasma in thermonuclear reaction.

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