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Sudden Jumps, Hysteresis, and Negative Resistance in an Argon Plasma Discharge

II. Discharges in Magnetic Fields

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Abstract

Experimental observations on the behavior of low-pressure, thermionic argon discharges in magnetic cusp and mirror configurations are presented. $I-B$ characteristics showing jump and hysteresis behavior were found. In some cases, the sudden sharp decreases in discharge current that were observed were preceded by the onset of coherent, low-frequency plasma oscillations, suggesting the possible role of instabilities.

1. Introduction

There is a vast literature, dating from the turn of this century, on the behavior of high-pressure ($\approx 0.1-10$ Torr) gaseous discharges. The properties of low-pressure ($\approx 10^{-5}-10^{-3}$ Torr) discharges have come under scrutiny only more recently. In particular, the behavior of low-pressure, gaseous discharges in a magnetic field is not completely understood. In the first of these two papers (identified as Part I), we presented observations on the behavior of a low-pressure argon discharge without a magnetic field, with emphasis on the sudden jump and negative resistance properties. A physical model was presented in order to shed some insight into the causes of this negative resistance. In Part II, we focus on the behavior of the argon discharge with a magnetic field present, either of a cusp or weak mirror configuration. Our main concern in Part II is the exposition of the $I-B$ characteristics of these discharges. We begin by giving a brief review of some of the previous work on plasma discharges in magnetic fields, particularly cylindrical columns in axial magnetic fields.

Some of the first observations of sudden jump and hysteresis behavior in plasmas came in connection with work on the helical instability of the positive column in a magnetic field [1–5]. Imazu et al. [1] observed a hysteresis effect near the critical magnetic field above which the positive column was unstable. The effect depended upon the neutral pressure and discharge current. A similar observation was made by Robertson and Curie [3] who noted an explosive onset of the helical instability, with hysteresis, when the longitudinal magnetic field of the positive column was increased above some critical value. This hysteresis effect was predicted by Holter and Johnson [6] and was due to the paramagnetic effect induced in the plasma when the helical instability was present.

The experiments on the positive column in a magnetic field were carried out at relatively high-neutral pressures (0.1–1 Torr) and are characterized by $\Omega_i \tau_{in} \ll 1$, where Ω_i is the ion gyrofrequency and τ_{in} is the ion-neutral collision time. More recently low-pressure cylindrical discharge plasma devices with a longitudinal magnetic field have been developed for basic plasma physics studies [7]. In one version of such a device at a pressure $p \sim 10^{-3}$ Torr ($\Omega_i \tau_{in} \sim 1$), Ellis et al. [8] reported observations of the onset of a large-amplitude, coherent plasma oscillation as the discharge voltage was increased. If the magnetic field was changed, the oscillation would disappear, but a different frequency and mode would onset. The instability was identified as a collisional drift instability.

Sudden jumps and hysteresis in the discharge current vs magnetic field ($I-B$) characteristics of a low-pressure ($p \simeq 10^{-4}$ Torr), relatively high field ($B \gtrsim 1$ kG) device have recently been reported [9, 10]. These observations were made in a cylindrical argon discharge generated by a conical spiral hot cathode. In these experiments, a sudden downward jump in discharge current occurred if the magnetic field was increased beyond a critical value. If the field was then decreased, the discharge current would return to its high value for a value of B less than the critical field at which the downward jump occurred. The downward jump in discharge current (and density) was accompanied by a substantial modification of the radial density profile and the onset of a large-amplitude, coherent plasma oscillation, propagating in the azimuthal sense. The instability was not identified. Recently, extensive observations of plasma and discharge characteristics of a cylindrical cathode discharge in a magnetic field have been reported [11, 12].

The present work extends our observations of sudden jump and hysteresis phenomenon in discharges in a magnetic field in an entirely different magnetic configuration, although similar behavior was observed. In the next section (2) the experimental results are presented. A discussion of the observations follows in Section 3, with concluding remarks given in Section 4.

2. Experimental Results

The discharge device used for the investigation has already been described in Part I, which dealt with the magnetic field-free case. To produce the magnetic field two water-cooled coils 23 cm diameter were used, carrying currents up to 1000 A (see Fig. 1 of Part I). Each coil consists of six turns of 6.35 mm copper tubing with teflon insulation and enclosed in an aluminium shell which could be grounded, floating, or biased. The electrical potential of the coils had little effect on any of the plasma properties. Depending on the sense of current in the coils either a magnetic cusp, or weak mirror (mirror ratio 1.2) could be produced. For the cusp configuration, the maximum field in the ring cusp (between the coils) was 100 G. The same filament structure described in Part I was used in the present set of experiments. For the magnetic cusp experiments, the filaments were located in the center of the two coils (i.e., in the field-null region), while for the mirror experiments they were located at various positions along the axis of the mirror. For these experiments an argon-neutral pressure in the range of $10^{-5}-10^{-4}$ Torr was used. The $I-B$ characteristics at various pressures for discharges in the magnetic cusp configuration are shown in Fig. 1. Sudden upward jumps in discharge current (and corresponding plasma density) were observed when the magnetic field was increased beyond a critical value dependent on the gas pressure. As shown in Fig. 1 the critical field for upward jumps increases with decreasing pressure. A hysteresis effect is also observed when the field is subsequently lowered below the critical value. It thus appears that for a given pressure, a high- and low-discharge state exists depending on the cusp magnetic field. The magnitude of the change in discharge current between the low and high states also depends upon the filament temperatures and the number of filaments used in the array, the largest jumps occurring when many filaments are used.

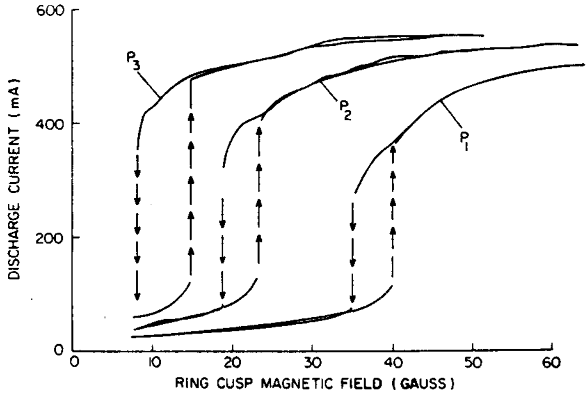

Fig. 1. $I-B$ characteristics for argon discharges in the magnetic cusp configuration. Discharge parameters: discharge voltage, $V_d = 60$ V, $P_1 = 2 \times 10^{-5}$ Torr, $P_2 = 3 \times 10^{-5}$ Torr, $P_3 = 4 \times 10^{-5}$ Torr

With the sense of magnetic coil currents properly adjusted, we were able to investigate the behavior of discharge in solenoidal (weak magnetic mirror) B field configurations. As in the previous cusp configuration, the cylindrical filament array was used as the cathode with the large stainless steel chamber as the anode for these configurations. In this solenoidal field configuration, the filaments are in a region of relatively strong magnetic field, as compared with the cusp configuration where the filaments were located in the null-field region. The $I-B$ characteristic for the weak mirror configuration are shown in Fig. 2. When the magnetic field was increased from zero, an upward jump in discharge current was observed ($A \to B$), but as the magnetic field was increased further, the discharge current reached a maximum and then gradually decreased ($B \to C$). This gradual decrease in discharge current was accompanied by the onset of coherent, low-frequency ($\sim$ 20 kHz) plasma oscillations. When the magnetic field was increased further, a downward jump in discharge current would occur ($E \to F$). If the magnetic field was then decreased, a hysteresis effect was again apparent in the $I-B$ characteristic.

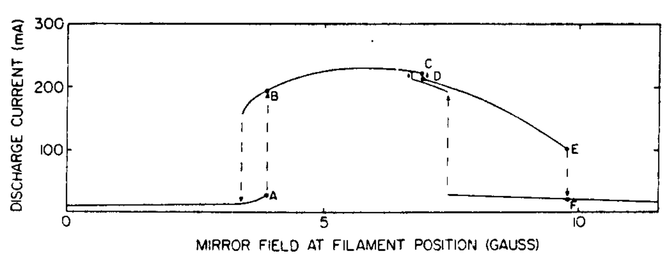

Fig. 2. $I-B$ characteristics for an argon discharge in the magnetic mirror configuration. Discharge characteristics: $V_d = 70$ V, $P = 6.5 \times 10^{-5}$ Torr

When the magnetic field was held constant at a value near a jump, jumps could be induced by varying the discharge voltage, pressure, or filament temperature; an upward jump resulting when these parameters were increased.

3. Discussion

Plasma confinement in a magnetic cusp is limited by the so-called 'leak-width', i.e., the cusp aperture through which the plasma escapes along the open field lines. This leak width varies inversely with B (see, e.g., Haines [13]). In this case the effect of the magnetic field on plasma confinement is analogous, in the field-free case, to the role of neutral pressure on plasma production. In addition, in the cusp configuration, both variables (B and p) have little effect on filament properties (see Part I). Thus the observed jumps and hysteresis while varying the cusp B field can be understood, by similar reasoning, by replacing the pressure, P, by the magnetic field strength B. Filament characteristic curves can be obtained by varying B, while plasma production curves obtained, as in Part I, by varying filament temperatures with fixed B. The results are nearly identical to the results in which pressure was varied and can be described by the some model, replacing P with B. This is similar to the well-known effect that a transverse magnetic field can lead to an apparent increase in pressure (see, e.g. Kostin et al. [14]), although our experiments have been conducted at lower gas pressures.

The observations of sudden downward jumps in discharge current as the magnetic field is increased (cf. $E \to F$ in Fig. 2) are similar to our earlier observations [9, 10] in a cylindrical (high-field) device. For a fixed magnetic field the jump and hysteresis when other variables (p, T_f, V_d) are changed are similar to those which occur when $B = 0$, and can be described by the type of curves discussed in Part I.

The behavior of the system as the mirror field is varied is more complex. In this case the filament and plasma production curves may both be affected by the magnetic field since the filaments are no longer in a field-free region. The observations of sudden decreases in discharge current associated with the presence of low-frequency plasma noise suggests the onset of a magnetic field related instability, leading to a decrease in confinement, as the magnetic field is increased.

In the mirror configuration, the presence of even a relatively weak B field may have a significant effect on the orbits of the primary ionizing electrons. (The primary electron gyroradius in the mirror configuration is $\sim$ few cm.) Under these conditions, the filament properties cannot be described by a function $I(n)$ as in Part I. This view of the effect of the magnetic field on the filament properties is supported by the observation that, in the cusp configuration, similar $I-B$ characteristics (as compared to the mirror case) are obtained when the filaments are moved along the axis from the null-field region into a region of stronger magnetic field.

4. Concluding Remarks

We have presented observations on the behavior of low-pressure, thermionic discharges in magnetic cusp and mirror configurations. These data suggest that certain nonlinear processes may be triggered by the presence of the magnetic field giving rise to sudden jump behavior in the discharge characteristics.

These observations have certain similarities with the onset of the beam-plasma discharge (see, e.g., Smullin [15]). The beam-plasma discharge sets in when the current of an electron beam injected into a neutral gas exceeds a certain critical value. For a fixed discharge current, as in our experiments, the magnetic field may either induce (or terminate) the onset of the beam-plasma discharge. Our experimental set-up differs, however, from the standard beam-plasma experiments. First, there is no well-defined electron beam, rather a diffuse stream of primary electrons emitted by the filaments.

Second, the energies of the primary electrons are usually ~ 70 eV, whereas most beam-plasma discharge experiments use keV electron beams.

In summary, we have presented in Part II experimental evidence on the influence of a magnetic field on the characteristics of low-pressure discharge. We have also shown that under certain circumstances the type of analysis introduced in Part I (filament and plasma production characteristics) can be applied to obtain some understanding of the role of the magnetic field. However, for the case of the filaments in the magnetic mirror configuration, the magnetic field appears to have a direct affect upon the filament characteristics, and the analysis of Part I cannot be used. Any analysis of this type of configuration must take these effects into account, as well as the possibility of the effect of magnetic field related instabilities on plasma confinement.

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