Hysteresis in a low-pressure argon discharge

Robert L. Merlino and Steven L. Cartier
Department of Physics and Astronomy, The University of Iowa, Iowa City, Iowa 52242

(Received 15 June 1983; accepted for publication 12 October 1983)

Hysteresis in the discharge characteristics of a low pressure ($p \simeq 10^{-4}$ Torr), magnetized argon plasma column is reported. The hysteresis is associated with sudden jumps in plasma density and discharge current as either the discharge voltage or magnetic field strength is varied. A substantial change in the plasma density profile and the appearance of coherent plasma oscillations are also observed.

PACS numbers: 52.80.Sm, 52.35.Py, 52.25.Lp, 51.50. + v

Plasma discharges often exhibit nonlinear and turbulent behavior.[1] Discharge devices have been used for basic plasma physics studies,[2,3] as ion sources in neutral beam injectors,[4] and for applications in reactive plasma etching.[5] An instability in high-pressure ($p \sim 0.01$–1 Torr) gas discharges, which exhibits hysteresis, is well documented and has been reviewed by Nedospasov,[6] for example. Here we report hysteresis effects observed in a low-pressure magnetized argon plasma column (i.e., where both the plasma electrons and ions are magnetized).

The observations were made in the device shown in Fig. 1. The plasma is produced by a discharge drawn from a hot tantalum conical spiral cathode ($V_F \simeq 30$ V, $I_F \simeq 95$ A) to a grounded anode mesh (16 lines/cm) located in the fringing field of the solenoid. The plasma properties were measured using three movable disk (1.6 mm diameter) Langmuir probes located in the central aluminum vacuum chamber.

Hysteresis in the discharge current I_D vs cathode bias voltage V_B, is shown in Fig. 2 for a fixed neutral argon pressure ($p = 2\times10^{-4}$ Torr) and magnetic field strength ($B = 730$ G). As the cathode bias voltage is increased from zero, I_D slowly increases until a critical voltage V_1 is reached, where I_D abruptly jumps from 0.3 to 1.3 A. When V_B is lowered from any value greater than V_1, I_D remains high until a second critical voltage $V_2 < V_1$ is reached. We refer to the high and low current discharges as the *upper* and *lower* states, respectively. Note that in this particular example, there is an intermediate transition at $V_B = 60$ V. Under certain conditions several closely spaced intermediate states are found, usually when decreasing V_B, although we have not studied these in detail. Several cycles of the hysteresis loop are shown to indicate that the effect is indeed reproducible. These sudden jumps with hysteresis may be interpreted as due to the onset of a negative differential resistance (dV_B/dI_D) in the discharge. Since the overall external resistance in the discharge circuit is small ($< 10\,\Omega$), a jump occurs when the differential resistance passes through zero. In some cases, with an external series resistor of several hundred ohms in the discharge circuit, we observed an S-shaped curve connecting the upper and lower portions of the I_D vs V_B characteristic.

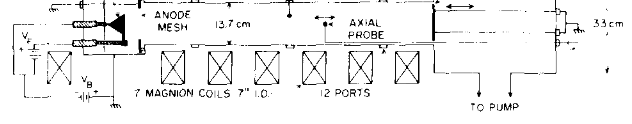

FIG. 1. Schematic diagram of plasma discharge device.

Figure 3 shows the hysteresis effect in the I_D vs B curve for a fixed p and V_B. At low fields the plasma is in the upper state and I_D initially increases with increasing B. When the magnetic field is increased to a critical value $B = B_2$, the plasma jumps to the lower state. If B is then reduced, the plasma will remain in the lower state for $B < B_2$ until $B = B_1$, when the plasma jumps back to the upper state. In some cases we have observed a hysteresis loop covering 1.5 kG.

We have also observed a significantly different plasma density profile $n(r)$, after the plasma jumps between the upper and lower states. This is evident in Fig. 4, where the profile of the electron saturation current drawn to a positively biased Langmuir probe, located in the center section of the main chamber, is shown. At low fields the profile is relatively smooth and, as expected, becomes more peaked with increasing B. For $B \leqslant B_2 = 1100$ G, the plasma is in the upper state and exhibits no unusual behavior as B is varied. But, when B is increased above 1100 G, an abrupt transition to the lower state occurs, where the time-averaged plasma profile peaks off axis. Note the existence of two significantly different profiles for $B = 810$ G, dependent only on the path taken. The densities at $r = 0$ corresponding to the upper and lower states are $n_{e,u} \simeq 6\times10^{10}$ cm^{-3} and $n_{e,l} \simeq 9\times10^9$

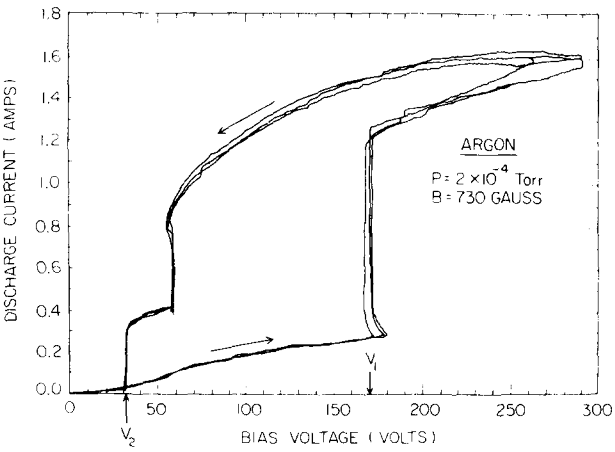

FIG. 2. Discharge current vs bias voltage.

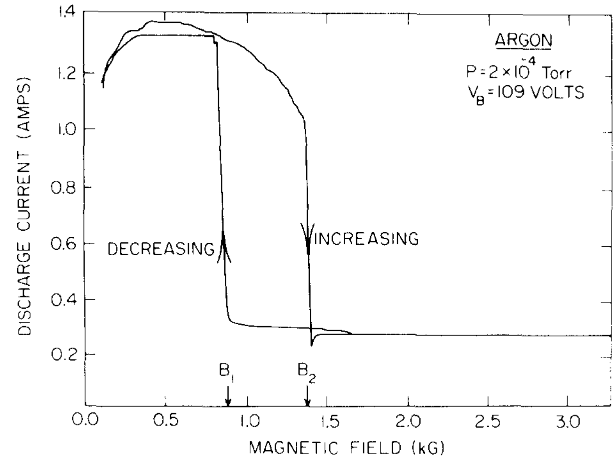

FIG. 3. Discharge current vs magnetic field.

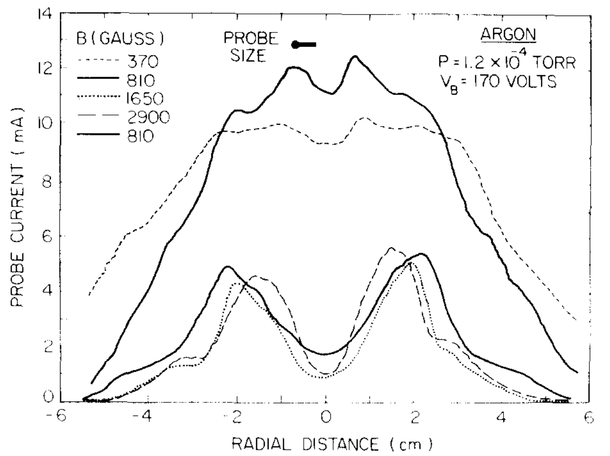

FIG. 4. Radial profile of electron saturation current ($\propto$ density) vs magnetic field ($B_1 = 600$ G, $B_2 = 1100$ G).

cm^{-3}, with $T_e \simeq 3$ eV in both cases. Although plots of electron saturation current are shown, actual plasma density profiles are not significantly different.

The transition from the upper to the lower states is accompanied by the onset of intense, coherent oscillations in plasma density with frequencies around 30 kHz. These oscillations are typically about 20 dB above the background power level and have a narrow bandwidth. Power spectra with up to five harmonics are sometimes observed in the region $B_1 < B < B_2$. Typically we observe $m = 1$ or $m = 2$ modes, depending on the tuning of the parameters p, V_B, and B which propagate azimuthally in the direction of the electron diamagnetic drift. Preliminary measurements of the parallel wavelength indicated that it was on the order of twice the machine length.

To summarize, we have observed significant hysteresis effects associated with abrupt transitions in discharge current and plasma density in a low-pressure, magnetized plasma column. Also we have observed coherent plasma modes associated with the hysteresis. It is not surprising that we find both sudden jumps *and* hysteresis effects.[1]

The effects observed here may be related to two other discharge effects known to exhibit hysteresis. One occurs in plasma discharges, without a magnetic field, which are irradiated by microwaves.[7,8] As the incident power is increased, nonlinear behavior in plasma density is observed with hysteresis. These effects have been attributed to nonlinearities in the ionization process.

The second effect was observed by Hoh and Lehnert[9] in a high-pressure positive column. This instability, known either as the helical instability or current-convective instability, was explained by Kadomtsev and Nedospasov.[10] The occurrence of our sudden transitions may be related to the onset of the helical instability as the magnetic field is increased above a critical value. The helical instability, however, has usually been observed in plasmas with collisionally dominated ions, whereas in our case, $\Omega_i \tau_{\text{in}} >> 1$ (Ω_i = ion gyrofrequency, τ_{in} = ion-neutral collision time), and in fact the observed oscillations are close to the argon ion cyclotron frequency as well as the diamagnetic drift frequency. The ion-cyclotron instability, however, should give rise to waves propagating radially out rather than azimuthally.

Hysteresis effects were also observed in experiments when the helical instability was present,[11] although the explanation[12] due to paramagnetic effects would not explain the large hysteresis effect that we have observed.

We acknowledge useful discussions with N. D'Angelo and K. Lonngren, and the technical assistance by A. Scheller. This work was supported by a Northwest Area Foundation Grant of the Research Corporation and by the United States Office of Naval Research under contract N00014-83-K-0452.

[1] See, e.g., B. B. Kadomtsev, *Plasma Turbulence* (Academic, New York, 1965).
[2] W. Gekelman and R. L. Stenzel, Rev. Sci. Instrum. **46**, 1386 (1975).
[3] G. A. Navratil, J. Slough, and A. K. Sen, Plasma Phys. **24**, 185 (1982).
[4] Y. Oka and T. Kuroda, Appl. Phys. Lett. **34**, 134 (1979).
[5] V. J. Minkiewicz, M. Chen. J. W. Coburn, B. N. Chapman, and K. Lee, Appl. Phys. Lett. **35**, 393 (1979).
[6] A. V. Nedospasov, Sov. Phys.—Usp. **18**, 588 (1976) [Usp. Fiz. Nauk. **116**, 643 (1975)].
[7] H. C. S. Hsuan, R. C. Ajmera, and K. E. Lonngren, Appl. Phys. Lett. **11**, 277 (1967).
[8] G. A. Markov and V. E. Tsvetaev, Sov. Phys.—Tech. Phys. **18**, 54 (1973) [Zhur. Tekh. Fiz. **43**, 87 (1973)].
[9] F. C. Hoh and B. Lehnert, Phys. Fluids **3**, 600 (1960).
[10] B. B. Kadomtsev and A. V. Nedospasov, J. Nucl. Energy, Part C **1**, 230 (1960).
[11] H. S. Robertson and E. H. Currie, Phys. Fluids **12**, 200 (1969).
[12] O. Holter and R. R. Johnson, Phys. Fluids **8**, 333 (1965).