PHYSICAL REVIEW E VOLUME 54, NUMBER 2 AUGUST 1996

Spatiotemporal patterning of a transverse ionization instability in annular rf discharges

Ji-Bin Du, Chi-Hui Chiang, and Lin I
Department of Physics, National Central University, Chungli, Taiwan 32054, Republic of China
(Received 20 December 1995)

The self-organized spatiotemporal patterns through a transverse ionization instability in a medium pressure annular rf glow discharge similar to a reaction-diffusion system is investigated. The formation of traveling periodic patterns through the spontaneous symmetry breaking process, the transient bifurcation behavior with wave number selection, the particlelike behavior of ionization clumps, and the effects of surface defects and external magnetic field are reported. [S1063-651X(96)04608-9]

PACS number(s): 52.35.Lv, 47.54.+r, 52.90.+z

In recent years, pattern formation in various nonlinear extended systems driven far from equilibrium, such as fluids, lasers, and chemical systems has been a topical research area. The formation of self-organized spatially coherent stationary or traveling structures through spontaneous symmetry breaking processes, and other interesting phenomena such as the wave number selection, phase defect formation, transient bifurcation behaviors, etc. have been studied [1–9]. Plasma systems consist of many charged species interacting through long range forces. Regardless of the complexity, recent studies also demonstrate that plasmas exhibit many interesting universal nonlinear behaviors from order to chaos [10–12]. However, the experimental studies in plasma systems are mostly made from point measurement for the temporal behaviors. Only few studies show that solitary patterns can be formed in highly dissipative plasma systems [13]. The formation of the spatially periodic pattern through the spontaneous symmetry breaking process in a highly symmetric plasma system has never been addressed. In this paper, from the point of view of pattern formation, we report a study of the generic spatiotemporal patterning behavior of a slow transverse ionization instability in a medium pressure cylindrical symmetric discharge system using a video imaging system.

A glow discharge can be generated at pressures from a few mTorr to a few tens of Torr by applying an electric field crossing two electrodes [14,15]. Basically, it is a weakly ionized plasma system far from equilibrium. Its ionization and recombination processes are similar to reactions in chemical systems, and provide feedbacks for the instability [8,15,16]. The diffusive transport similar to that in a reaction-diffusion system [8] and the additional drift transport induced by the space charge field fluctuations provide spatial coupling, and lead to the formation of spatiotemporal ionization instability [16]. The large amplitude low speed striations with large bright and dark domains found many decades ago in linear dc discharge tubes are good examples for the longitudinal (i.e., the wave number K is in parallel with the direction of the driving electric field) ionization instability [15,16]. A localized current density filament was also found recently in a narrow transverse gap operated in the dc and low frequency ac modes [13]. However, those systems do not possess good symmetry for testing the spontaneous symmetry breaking and bifurcation process for the periodic pattern.

In our previous experiments, we found a transverse (the wave number is normal to the driving electric field) $\mathbf{E}\times\mathbf{B}$ drift type ionization instability with high speed (10^4–10^5 cm/sec) in rf magnetodischarges in the annular gap between two concentric cylindrical electrodes and studied its generic nonlinear and chaotic behaviors using two Langmuir probes [11,12]. In this experiment, we remove the axial magnetic field and increase the pressure from a few mTorr to a few hundreds of mTorr in a similar system. The high pressure makes the system highly collisional and slows down the transport process. A new low speed transverse periodic ionization patterning can be visually observed from the emitted light. Since the system is driven radially, it has good rotational symmetry. The absence of the axial B field further resumes the parity symmetry (for the clockwise and counterclockwise rotations) of the system. It provides an environment with a high degree of symmetry for studying the generic nature of pattern formation in a dissipative plasma system. In this work, the formation of traveling waves through the spontaneous symmetry breaking process under the variation of system control parameters is studied. The wave-number selection, the first order bifurcation with hysteresis behavior, the particlelike behavior, and the effects of the external magnetic field and electrode boundary defect are investigated.

The experiment is carried out in an rf cylindrical discharge system as reported elsewhere [17]. Figure 1 shows the

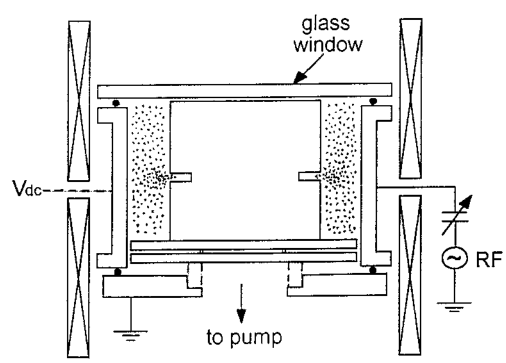

FIG. 1. Sketch of the side view of the cylindrical discharge system.

1063-651X/96/54(2)/1829(4)/$10.00 54 1829

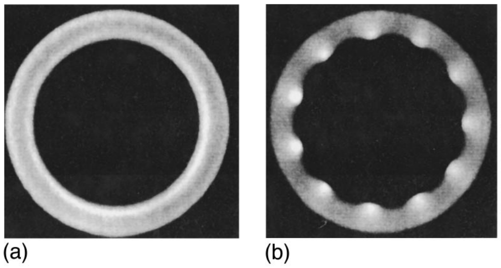

FIG. 2. The light emission distribution of the typical patterns in the annular discharge at 8-W rf power. (a) $m = 0$ at 450 mTorr; (b) $m = 11$ at 600 mTorr.

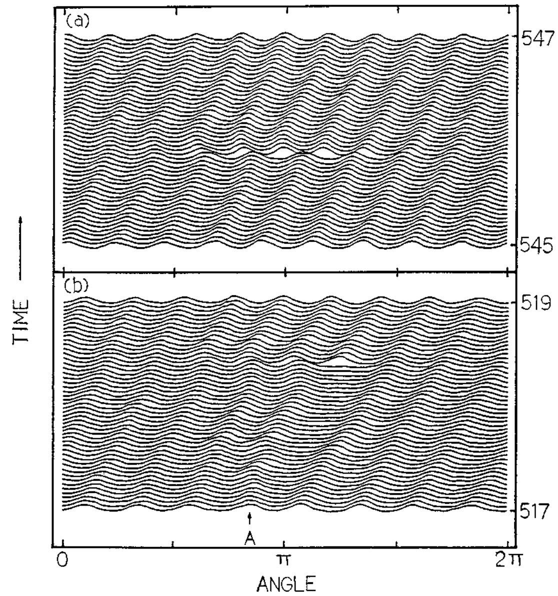

FIG. 3. The space-time diagrams of the clockwise traveling patterns with 0.2-sec time step at 8-W rf power. The pressure is linearly ramped. (a) With m from 9 to 10 bifurcation. (b) With m from 8 to 9 bifurcation. The modulational instability and local phase defect in (a) and (b), respectively, are associated with the surface defect at point A.

side view of the system. It consists of a hollow outer electrode with a 9-cm diameter and capacitively coupled to a 14-MHz rf power system, and a grounded center electrode with a 6-cm diameter. The system is operated with a few hundred mTorr Ar gas. A uniform weak axial magnetic field (a few G) can be applied if necessary. A weakly ionized low temperature steady-state rf discharge is sustained between the electrodes. The discharge emission intensity (which increases with the electron density) distribution over the horizontal plane (integrated along the axial direction) is monitored by a video camera 2.5 m above the system through the top glass window and is digitally processed.

Radially, the discharge can be divided into the nonuniform dark space regions adjacent to the electrode surfaces and a glow region between the two dark space regions [14]. The former are about 1–4 mm thick and support large electron density gradient and strong rf-induced dc electric field. An annular groove with 3-mm height is cut along the surface of the center electrode to localize the axial position of the instability and to reduce the rf power for the onset of patterning by the strong local electric field and the high ionization rate due to the hollow electrode confinement effect in the groove.

Figure 2 shows the spatial distribution of discharge emission intensity in the plane normal to the axial direction. Figure 2(a) is the typical distribution without any azimuthal patterns in the low pressure regime. The emission is mainly from the glow region with the strongest intensities (i.e., highest ionization or electron density) near the two electrodes. The weak emission from the dark space region between the glow region and electrodes can be hardly observed in the figure. Figure 2(b) shows the typical periodically distributed bright and dark regions around the center electrode at higher pressure.

Basically, higher pressure and rf power are required for the formation of patterns. The onset of patterning is associated with a periodic pattern. For a defect free electrode surface, the pattern rotates either clockwise or counterclockwise depending on the initial fluctuation at the onset. Figures 3(a) and 3(b) show the space-time diagrams of the emission intensity of the traveling wave (with a slow linear ramping of system pressure for studying the bifurcation). The signal is taken from the video image along a concentric circle 6 mm away from the center electrode boundary. The direction of rotation can be reversed after applying a short pulse of external perturbation, e.g., a short pulse of axial magnetic field with a few G.

Figure 4 shows the bifurcation diagram with the hysteresis behavior of the changes of V_{dc} and the mode number m (the number of bright regions) as system pressure P changes at rf power = 8 W. V_{dc} is the rf induced dc floating potential of the outer electrode, which is a function of the state of the discharge [14]. m is discrete and jumps abruptly from 0 to 8 as the pattern onsets. V_{dc} varies slightly and m remains constant until the next bifurcation. Each further forward bifurcation is also subcritical and associates with m

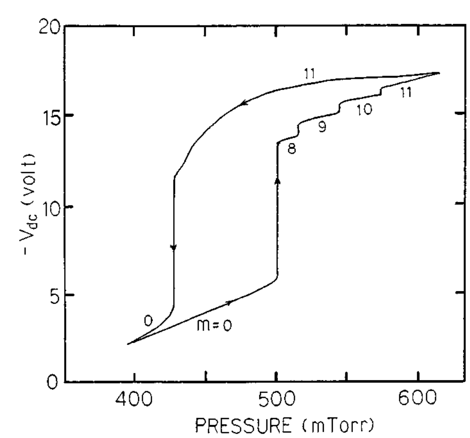

FIG. 4. The bifurcation diagram of changing pressure at 8-W rf power.

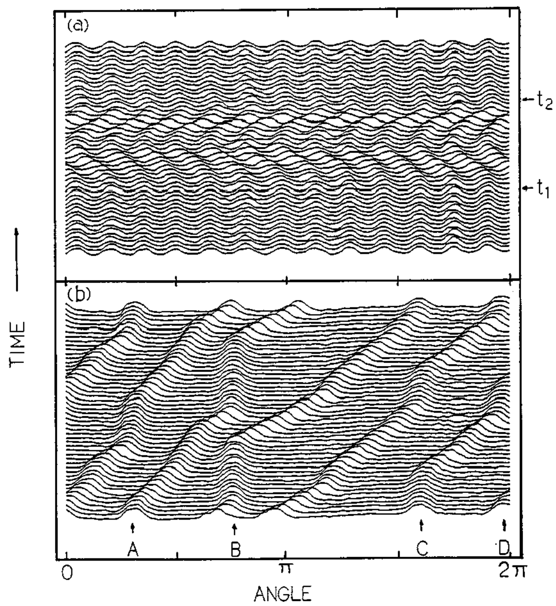

FIG. 5. (a) The space-time diagram (with 0.5-sec time step) of the forced rotations by applying a single period of sinusoidal pulse of the axial magnetic field (with 12-G amplitude and 10-sec period) on a defect locked stationary pattern with $m=13$. The start and end of the pulse are indicated by t_1 and t_2, respectively. (b) The evolution (with 1-sec time step) of the particlelike ionization clumps under a dc axial magnetic field (6 G). The electrode surface defects at A, B, and C cause trapping.

increasing by one. Large m up to 25 has been observed at high P. Modulating rf power shows the similar hysteresis behavior. However, at a fixed P, m increases by one or two with a large increase of rf power.

Figure 3(b) shows the typical transient behavior of the bifurcation process with m jumps from 8 to 9. The electrode surface defect due to the contamination at point A causes the retarding of the motion of the bright bumps and eventually leads to the formation of a large phase defect and bifurcation, as the intrinsic wavelength scale reduces with increasing P. The retarding effect becomes less local at higher m. For example, in Fig. 3(a), the 9 to 10 bifurcation is more similar to a bifurcation with a long wavelength modulational Eckhaus instability [5], but still with the extra bump emerging around the defect site.

The electrode surface defects can affect the surface secondary electron emission rate and can retard the rotation or pin the entire pattern. For a defect free surface, applying a weak axial magnetic field breaks the parity symmetry and forces the traveling pattern to move along the $\mathbf{E}\times\mathbf{B}$ direction (azimuthally) with higher speed but the same wave number. It can also force the defect locked stationary pattern to a rotational mode. Figure 5(a) shows the defect pinned stationary pattern and its forced rotation with two opposite directions by applying a single period of sinusoidal pulse of the axial magnetic field.

The system also exhibits interesting particlelike behavior. Figure 5(b) shows the dynamical behavior of five bright clumps at $B=6$ G. The five clumps are obtained by reducing rf power (can also be obtained by reducing pressure) along the upper branch of the hysteresis curve after the onset of the periodic pattern with $m=8$. They are stationary in the absence of magnetic field. Four electrode defects are introduced at points A, B, C, and D with the strongest one at B. The axial magnetic field causes the rotation of the clumps except those trapped by the defects. The moving clump is decelerated when it approaches the trapped clump. It eventually pushes the latter out of the trap and itself falls into the trap. Namely, the clumps are repulsive at short distance. Similar detraping of the clump by the adjacent clump was also found at the m from 8 to 9 bifurcation [Fig. 3(b)].

Solving the complicated Poisson equation and the balance equations of particle density, momentum, and energy for the instability is beyond the scope of this work. Basically, the radial rf electric field is the main source of feeding energy for this open dissipative system. The ionization and recombination are responsible for the growth and suppression of the local electron density, respectively, and the ambipolar diffusion process provides the spatial coupling. Unlike the convective Bénard cells or the Taylor vortices [1], the intrinsic wavelength scale L of our system can be controlled as a Turing structure [7,8]. It decreases with increasing P, which decreases the ionization, recombination, and transport mean free paths and causes wave-number selection under the periodic boundary condition with fixed circumference. Our periodic pattern can also be treated as a quasi-one-dimensional lattice containing many ionization clumps with short range repulsive force. The surface defect affects the rotational symmetry. A weak defect retards the local clump motion when clumps are loosely packed, and affects the entire lattice motion when they are more strongly coupled. This explains the emergence of the large local phase defect triggered by the surface defect at m from 8 to 9 bifurcation and the long wavelength modulational type bifurcation for the larger m. After each bifurcation, the modulation becomes less pronounced because clumps are tightly packed again.

In conclusion, we have directly observed a transverse ionization instability in a highly dissipative rf annular glow discharge system. Regardless of the complexity of the plasma, the system exhibits interesting dynamical patterning behaviors partially similar to other nonlinear extended systems. Traveling waves are formed through the spontaneous breaking of the parity and rotational symmetries. The periodic pattern can be treated as a lattice with many particlelike ionization clumps. Changing P causes the variation of L. Wave-number selection and the dynamical behavior of subcritical bifurcation accompanied by the emergence of a phase defect or modulation instability, and hysteresis behaviors are observed. The axial magnetic field and electrode surface defects affect the system symmetry and in turn the dynamical behaviors. The convenient time scale for video recording and the ability for controlling the intrinsic length scale provide us with a new environment to study the universal behavior of pattern formation, transient behavior, and phase dynamics in a different complicated extended system.

This work was supported by the Department of Physics, National Central University, and the National Science Council of the Republic of China under Contract No. NSC-83-0208-M-008-039.

[1] M.C. Cross and P.C. Hohenberg, Rev. Mod. Phys. **65**, 851 (1993).

[2] E.J. D'Angelo, E. Izaguirre, G.B. Mindlin, G. Huyet, L. Gil, and J.R. Tredicce, Phys. Rev. Lett. **68**, 3702 (1992).

[3] G. Grynberg, A. Maitre, and A. Petrossian, Phys. Rev. Lett. **72**, 2379 (1994).

[4] S. Rasenat, E. Braun, and V. Steinberg. Phys. Rev. A **43**, 5728 (1991).

[5] W. Eckhaus, *Studies in Nonlinear Stability Theory* (Springer, New York, 1965); A.J. Simon, J. Bechhoefer, and A. Libchaber, Phys. Rev. Lett. **61**, 2574 (1988).

[6] P. Coullet, C. Elphick, L. Gil, and J. Lega, Phys. Rev. Lett. **50**, 884 (1987).

[7] A.V. Gaponov-Grekhov and M.I. Rabinovich, *Nonlinearities in Action* (Springer, Berlin, 1992), Chap. 4.

[8] *Oscillations and Traveling Waves in Chemical Systems*, edited by D. Feld and M. Burger (Wiley, New York, 1985); V. Castets, E. Dulos, J. Boissonade, and P. De kepper, Phys. Rev. Lett. **64**, 2593 (1990).

[9] P. Kolodner, D. Bensimon, and C.M. Surko, Phys. Rev. Lett. **60**, 1723 (1988); P. Kolodner, *ibid.* **69**, 2519 (1992).

[10] T. Braun, J.A. Lisboa, and R.E. Francke, Phys. Rev. Lett. **59**, 613 (1987); Q.L. Wang *et al.*, *ibid.* **63**, 163 (1989).

[11] Lin I and M.S. Wu, J. Appl. Phys. **62**, 4077 (1987).

[12] J.H. Chu and Lin I, Phys. Rev. A **39**, 233 (1989); C.S. Chern and Lin I, *ibid.* **43**, 1994 (1991); Lin I and J.M. Liu, *ibid.* **46**, R733 (1992); Phys. Rev. Lett. **74**, 3161 (1995).

[13] H. Willebrand, T. Hunteler, F.-J. Niedernostheide, R. Dohmen, and H.-G. Purwins, Phys. Rev. A **45**, 8766 (1992); E. Ammelt, D. Schweng, and H.-G. Purwins, Phys. Lett. A **179**, 348 (1993).

[14] B. Chapman, *Glow Discharge Processes* (Wiley, New York, 1981).

[15] Y.P. Raizer, *Gas Discharge Physics* (Springer, Berlin, 1987).

[16] I. Grabec, Phys. Fluids **17**, 1834 (1974); L. Pekarek and V. Krejci, Phys. Lett. **81A**, 228 (1981); C. Redehaus, H. Willebrand, R. Dohmen, and F.J. Niedernostheide, Phys. Rev. A **45**, 2546 (1992).

[17] J.H. Jiang, J.B. Du, and Lin I (unpublished).