Physics Letters A 376 (2012) 2126–2133

Contents lists available at SciVerse ScienceDirect

Physics Letters A

www.elsevier.com/locate/pla

Study of transverse and longitudinal bifurcation for pattern formations of a plasma column

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ARTICLE INFO

Article history:
Received 25 November 2011
Received in revised form 27 April 2012
Accepted 4 May 2012
Available online 9 May 2012
Communicated by F. Porcelli

Keywords:
Plasma column
Surface wave
Bifurcations
Striations
Two-step ionization
Diffusion equations

ABSTRACT

In experimental investigations array, helical and spiral patterns of a plasma column are formed by changing the operating parameters e.g., input power, working pressure, drive frequency, diameter of the glass tube, background gases, etc. Further, theoretical formulations are attempted using a hydrodynamic model to explain the bifurcation of a plasma column in the transverse and longitudinal axis considering two-step ionization in surface wave produced plasma. Findings of this study reveal that metastable atoms provide two-step ionization which in turn excites weak instability, which bifurcate plasma column in such a way that different patterns are formed.

1. Introduction

Many systems show pattern formation if they are driven sufficiently far from equilibrium. Hence over a decade they attracted attention of experimental and theoretical investigations [1]. A large number of patterns are also observed in low-pressure glow discharge, which manifest as structured regular layers representing variations in the plasma density, density of excited state atoms, axial electric field and discharge current and are also called striations [2]. Striations in the sense of instabilities are common in occurrence in weakly ionized plasmas and have been most often studied in the context of direct current discharge in cylindrical geometries [2–7]. Striations have been studied in different plasmas with different discharge mechanisms such as DC-discharges [2–7], rf plasmas [8–10], laser plasmas [11], ionospheric plasmas [12] including pattern formations in low temperature plasmas [13–15]. Generally, on the basis of visual observations, two types of striations have been classified-standing or stationary striations (having static appearance) and moving striations (with a certain velocity) [16,17]. In spite of its long research history striations or patterns are not yet fully understood or classified because of their diverse phenomena [18]. To the best of our knowledge striations in terms of patterning in surface wave produced plasma are poorly studied by experimental and theoretical means [19]. Nevertheless surface wave driven plasma column has potential applications [20]. Therefore, this Letter is dedicated to the extensive study of pattern formation in surface wave produced plasma column. In the order of investigations, experiments are conducted to achieve different structures or patterns of a plasma column, which have well-defined geometrical shapes. For qualitative understanding of the visual observations, patterns are characterized by probe diagnostics. Moreover, formation of patterns in a plasma column are discussed using hydrodynamic models by solving two diffusion equations for electron density and metastable atoms in longitudinal and transverse axis to obtain the bifurcation parameters. Finally, it is shown that bifurcation parameter depends on operating parameters.

The manuscript is organized as follows. Section 2 presents experimental set-up, Section 3 deals with the measurements and results, Section 4 gives discussion and finally Section 5 concludes the study.

2. Experimental set-up

A dedicated experimental set-up is designed and fabricated to study the pattern formations in surface wave produced plasma.

A schematic drawing of the experimental set-up for surface wave produced plasma column is shown in Fig. 1. In this set-up, a 30 cm long glass tube of diameter of 3 cm is evacuated by a combined system of rotary and diffusion pumps. The glass tube is then filled with argon gas to various working pressures. The glass tube is evacuated using a diffusion pump, at the lower end of the glass tube, with pumping speed of 250 l/min. The diffusion pump

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0375-9601/$ – see front matter
http://dx.doi.org/10.1016/j.physleta.2012.05.005

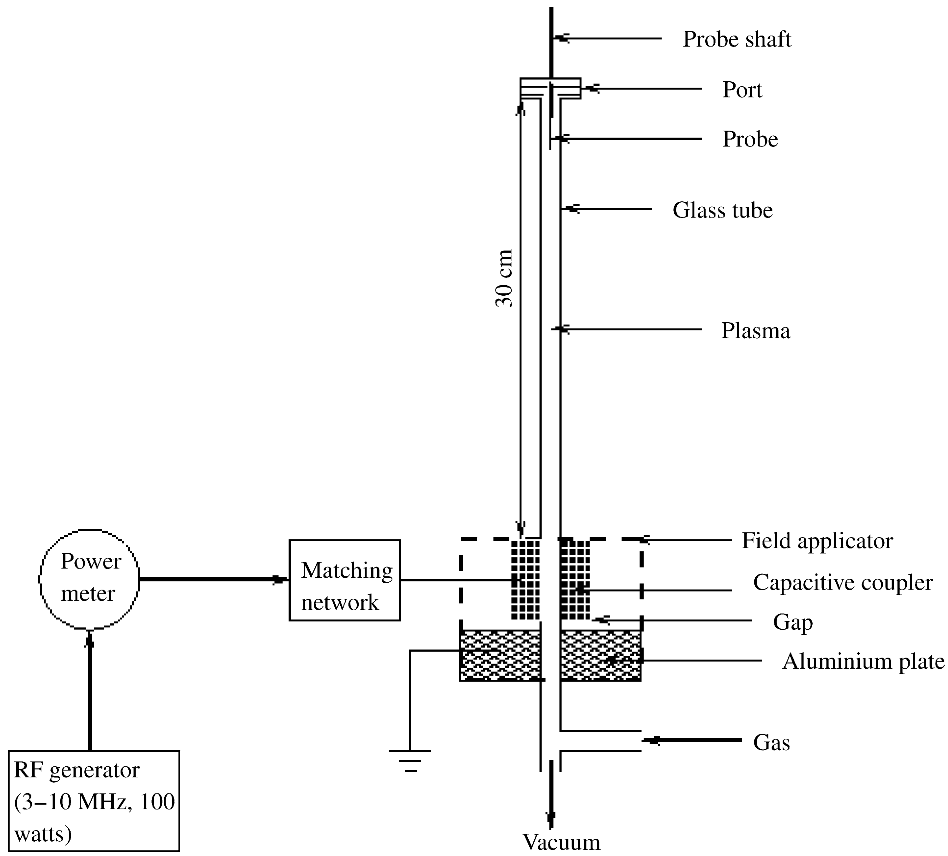

Fig. 1. Schematic of the experimental set-up for surface wave produced plasma column.

is backed by a rotary pump having a pumping speed of 200 l/min. A base pressure of around 1×10^{-4} mbar is achieved prior to the experiment and then neutral gas is injected in the glass tube using a fine needle valve to maintain the required operating working pressure. A capacitive coupler of width 35 mm is mounted 2 mm above (the ground plate is of diameter 120 mm, thickness 20 mm) and at one end of the glass tube. Sometime, arrangement of capacitive coupler and ground plate in the composite form is called field applicator because rf field is applied between them. The initial breakdown inside the tube in the gap between coupler and ground plate is initiated by a CW radio frequency generator operating between 3 MHz to 10 MHz up to 100 W power. The gap is varied from 1 mm to 5 mm and required power for initial breakdown varies from 10 W to 20 W at a working gas pressure of 0.01 mbar. An L-type matching network with variable inductors and capacitors is used to maintain the 50-Ohm impedance for the rf generator with and without plasma. The coupled power is measured with the help of a power meter. Outlined experimental set-up is made with the motivation to study the striations with the help of well-established experiments on striations in DC plasmas. Therefore, length and diameter of the glass tube are chosen in such a way that can suitably match with the operating parameters like input power, working pressure, frequency, etc and patterns in a surface wave produced plasma column can be achieved.

3. Measurements and results

3.1. Characterization of plasma column

It is well known that patterning of plasma can be governed by the discharge mechanism and operating parameters, therefore it may be quite interesting to study discharge mechanism for the formation of 30 cm long plasma column while rf power is fed at one end of the glass tube. The initial breakdown takes place in the discharge tube close to the gap in the field applicator. The gap is varied from 1 mm to 5 mm and the required power for initial breakdown varies from 10 W to 20 W. It is also observed that 300 V potential difference is required to form the plasma. Due to the field gradients within the gap region in the field applicator, electrons are driven along the tube axis by rf field [20]. Briefly, the properties of surface wave discharge depend on the amount of power absorbed per unit length of the plasma and on the discharge conditions e.g. tube dimension, material, operational frequency, input power, working pressure, composition of the filled gas, wall material of tube and the mode number [20]. Similarly it is highly possible in our experiment that the surface wave gets excited at axial position and propagates in z-direction, the power flux of the wave decreases with increasing z as the power is gradually expanded in sustaining the discharge. The plasma column ends where wave power drops below the level necessary to sustain the plasma. The power dissipated per unit length of the plasma column varies along the axis of the glass tube. The axial distribution of the high frequency electric field, $E(z)$, gives directly the value of the attenuation constant of the surface wave [21]. The power is lost by electrons through collisions with the ions and neutrals. With reference of above, the length of plasma column with input power is measured keeping constant other operating parameters. The length of plasma column is varied from 5 cm to 30 cm with input power up to 36 W at constant working pressure of 0.02 mbar and driven frequency of 5 MHz. This study reveals that 30 cm long plasma column is formed by surface wave discharge. Plasma column is characterized using the standard cylindrical Langmuir probe. In such Langmuir probe, a tungsten probe tip of length 5 mm and diameter of 0.5 mm is spot welded in the central conducting wire of semi-rigid coaxial cable of outer of 3.6 mm. The probe shaft is made of stainless steel (SS) and is pushed up to the