Spatial structures arising along a surface wave produced plasma column: an experimental study

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Abstract. The formation of spatial structures in high-frequency and microwave discharges has been known for several decades. Nevertheless it still raises increased interest, probably due to the variety of the observed phenomena and the lack of adequate and systematic theoretical interpretation. In this paper we present preliminary results on observation of spatial structures appearing along a surface wave sustained plasma column. The experiments have been performed in noble gases (xenon and neon) at low to intermediate pressure and the surface wave has been launched by a surfatron. Under these conditions we have observed and documented: i) appearance of stationary plasma rings; ii) formation of standing-wave striation-like patterns; iii) contraction of the plasma column; iv) plasma column transition into moving plasma balls and filaments. Some of the existing theoretical considerations of these phenomena are reviewed and discussed.

1. Introduction

Observations of plasma structures (sometimes called “plasmoids”) in high-frequency (HF) and microwave discharges have been reported for many decades [1,7,8,12]. Some of them show partial similarity with the well known strata in DC discharges [2], but in most cases they demonstrate completely different features, presumably associated with the different physical processes involved, in particular, when their behavior is not necessarily determined by electrodes essential for the discharge existence.

The aim of this study is to present results on observations of spatial structures appearing in a surface wave (SW) sustained plasma column and to compare them with (some of the many) older and newer experimental and theoretical investigations. The paper is organized as follows. Section 2 contains a brief description of the experimental apparatus and the measurement technique used. The formation of static plasma rings along a SW sustained plasma column in xenon at low pressure is considered in section 3, while section 4 deals with the appearance of standing-wave striation-like structures, or stationary plasma balls. Sections 5 and 6 are devoted to observations of plasma column contraction and its transition into filaments, moving balls and strings of balls, respectively. Some considerations on the possible physical mechanisms involved in these rather complicated phenomena are made in Section 7.

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2. Experimental set-up and diagnostics
The experimental set up is shown schematically in figure 1. The plasma was produced in two types of
rasotherm glass tubes with internal/external diameters of 42 mm/46 mm and 22 mm/25 mm,
respectively. The experiments were performed by using stagnant spectrally pure xenon and neon at
pressure varying from several tenths of mTorr to several Torr (background pressure of the tubes being
less than $10^{-6}$ Torr). The surface wave was launched by a surfatron [3,4] at frequency of 510 MHz and
power of up to 100 W c.w. The reflected power was measured to be about 10 percent of the input one,
provided that the plasma column does not fill the whole tube.

![Figure 1. Schematic of the experimental setup](image)

As some of the diagnostics methods used have been previously reported in [5], we now concentrate
on those, essential for the present study. A movable optical system (consisting of lenses, slit aperture
and a photomultiplier) has been implemented to obtain axial profiles of luminosity along the plasma
column, while photo-densitometry has been applied to obtain the light emission intensity radial
profiles. The latter has been done by Abel inversion of the chord luminosity profiles to obtain the
corresponding radial profiles, assuming azimuthal symmetry, taking into account the logarithmic
dependence of photo-material density on exposition and making use of the known characteristics
(contrast, veil) of the photographic material used. Microwave electric field amplitudes (axial and
azimuthal components near the tube walls) have been measured by using two antennas, the movable
one capable of changing polarization and both of them calibrated for absolute measurements. These
antennas have been used for plasma SW interferometry, too. The photographs shown throughout the
study have been taken with a 35 mm photo camera by using standard ORWO NP negative films and
ORWOCHROM color slides.

3. Observation of static plasma rings
The formation of static plasma rings (figure 2) along a SW sustained plasma column has been
observed in the 42 mm i.d. tube in xenon within the 30 to 80 mTorr pressure interval. They are
amazingly stable and demonstrate no visible change even for time intervals exceeding 30 minutes. Our
observations include single rings and sets of rings, as well as azimuthally symmetric (figure 2) and
obliquely oriented with respect to the discharge axis ones (figure 3), the latter looking rather strange
for those who presume propagation of an azimuthally symmetric SW. It is worth noting that we were
unable to observe plasma rings in xenon in the 22 mm i.d. tube, or in neon either.
An axial profile of the luminosity for a set of azimuthally symmetric plasma rings is shown on figure 4. It reveals a spatial period of about 3 cm. We estimate electron density (from SW interferograms) as $1.1 \times 10^{11} \text{ cm}^{-3}$ (corresponding to SW wavelength of 45 cm) at the column origin and $3 \times 10^{10} \text{ cm}^{-3}$ (SW wavelength of 20 cm) at the column end, while the electron temperature from extrapolated probe measurements was found to be about 2 eV. The measured SW electric field amplitudes are as follows: axial component decreasing (from the exciter to the end of the column) from 4.5 V/cm to 0.2 V/cm for a 40 cm long column, azimuthal component decreasing from 1.5 V/cm to 0.2 V/cm for a 40 cm long column.
to 0.2 V/cm, respectively. Amplitudes decreasing from 0.2 V/cm to zero (noise level) for a distance of about 5 cm are detected for both components in the dark space immediately after the column end.

Further on, by using photo-densitometry combined with Abel inversion technique, we have obtained radial distributions of the light emission intensity in a slice corresponding to a maximum intensity within a ring (figure 5a) and in a slice corresponding to minimum intensity in the space between two rings (figure 5b). One may see that, apart from the difference in modulation depth, the radial profiles are very similar. The somewhat unexpected result raises additional questions concerning the nature of this phenomenon. In particular, “hollow” (maximum near the periphery) radial distributions of excited atoms, metastables and emission intensities of optically thin lines in noble gases (argon, helium, neon, argon-xenon, and argon-nitrogen mixtures) that more or less follow the radial dependence of the electromagnetic (surface) wave electric field components in the plasma region have been reported in [6]. In the same time the electron density (under the conditions of a diffusion-controlled discharge) should follow the well known Bessel radial profile. It is worth to note some contradiction in the most often used paradigms, applied for (almost) the same discharge conditions: i) luminosity proportional to plasma density [3], constant electron temperature radial profile (due to the high electron thermal conductivity) and ii) luminosity depending on electron temperature, the latter following the local electric field amplitudes [6]. These considerations might be useful for an attempt to formulate the basics, on which this rather strange longitudinal modulation (perhaps only visually appearing as rings) could be explained.

4. Formation of standing-wave striation-like patterns (stationary plasma balls)

These structures (often referred as plasma balls or stationary striations, [7–9]) have been observed in SW sustained discharge in xenon at 100 mTorr in the 22 mm i.d. tube (figure 6) in experimental conditions where the electromagnetic SW fills the whole tube and is (presumably) reflected from its end. Appearances of stationary plasma balls have previously been reported for various types of HF discharges. Studies on striation-like patterns in a HF (8 MHz) electrodeless discharge in krypton at pressures of 20 Torr and 74 Torr in 35 to 40 mm i.d. tube [7] indicate a decrease of plasma ball size and spatial period with increasing pressure at constant input power. Another observation of similar patterns is reported in [8] for a HF (87 MHz) electrodeless, weakly ionized, collision dominated, magnetized (the latter appeared to be unimportant [8,9]) argon discharge at pressure of 7.8 Torr. Special efforts have been made to ensure that the plasma balls appear under conditions, where two-stage ionization processes prevail, and vanish when a direct ionization only takes place. A plausible (in our opinion) interpretation resulting from the stability analysis of an appropriate set of partial differential equations that describes the excitation and ionization processes in the plasma, considers the observed plasma ball structures as a (primary) bifurcation phenomenon [9].

Similar experiments have been performed [10] in a microwave (2.45 GHz, up to 100 W c.w.) discharge sustained by SW excited by two coaxial cavities, in argon at pressures from 50 mTorr to 330 Torr, filling 4 and 7 mm i.d. tubes. In the latter experiment the “wavelength” of the standing-wave-like pattern increases with increasing pressure – a behavior that differs from the one described above and raises questions similar to those discussed at the end of Section 3.

Figure 6. Standing-wave-plasma-balls pattern (xenon 100 mTorr, 22 mm i.d. tube).

Figure 7. Contraction of a SW sustained plasma column (neon 100 mTorr, 22 mm tube)
5. Plasma column contraction and its splitting into filaments

Plasma column contraction is typical for intermediate and high pressure DC, HF and microwave discharges. In our experiments of a SW sustained plasma column [11] it is characterized by an abrupt appearance of a dense (luminous) core sharply distinguished from the relatively sparse (dark) background when increasing the pressure from 100 mTorr to 1 Torr. An example of such contraction in the 22 mm i.d. tube filled with neon at 100 mTorr is presented in figure 7; the estimated plasma density obtained from SW interferograms was \(1.4 \times 10^{10}\) cm\(^{-3}\) (corresponding to a SW wavelength of 12 cm) while the extrapolated electron temperature was about 4 eV. Further on, by using the 42 mm i.d. tube filled with xenon at pressure of 100 mTorr (estimated plasma parameters: plasma density varying from \(8.1 \times 10^{10}\) cm\(^{-3}\) (SW wavelength of 50 cm) to \(4.7 \times 10^{10}\) cm\(^{-3}\) (SW wavelength of 38 cm), electron temperature of 1.5 eV) we could observe contraction (figure 8) and splitting of a contracted plasma column into two filaments (figure 9). Sometimes a slow (characteristic time greater than 0.1 s) rotation of the single core or the split filaments takes place.

![Figure 8. Contraction of a SW sustained plasma column (xenon 0.1 Torr, 42 mm i.d. tube)](image1)

![Figure 9. Contracted plasma column split into two filaments (xenon 0.1 Torr, 42 mm tube).](image2)

Microwave discharges in the (rather unusual) form of filaments have often been reported, e.g. in [12], where a 10 GHz discharge in argon at 100 mTorr in a large vessel, consisting of at least 30 filaments (some of them split) and additional ball-like light spots, has been considered. The study [7] reveals that the rare gas atmospheric pressure microwave (2.45 GHz) discharges (in neon, argon, krypton and xenon, but not in helium!) at power between 10 and 100 W c.w. appear as “one or more separate and distinct discharge channels lying parallel to the electric field vector”. The increase in input power has as a consequence the increase of the number of discharge channels (filaments) rather than the diameter of a single channel [7]. Qualitatively the same behavior has been observed in the recent experiments in (standing) SW discharge in xenon [13] and in a pulsed 2.45 GHz surface-wave discharge in neon at atmospheric pressure [14]. In particular, the ionization front of a filamentary SW discharge has been found to exhibit a corona-leading-streamer-like behavior, while the observed (at lower pressures) highly luminous ionization front is associated with the presence of resonant absorption [13]. The contraction and filamentation phenomena reported in [14] are interpreted as a result of the non-uniform neutral gas heating and the (strongly non-uniform) electromagnetic wave penetration (due to the skin-effect) in the plasma. In our study [11], a theory has been proposed that predicts appearance of a density jump in the radial plasma density profile (in the vicinity of the critical density point) due to the ponderomotive effect of the SW (density profile modification). This point of view may find some support in the experimental studies and the modeling of electrode microwave (2.45 GHz) discharges [15], where the regions of the near-electrode bright plasma and the neighboring dark ones are characterized with overcritical (ratio of 2 to 5 times) and under-critical plasma density, respectively.

It is worth to be noted that several experimental studies (cf. [7,13]) contain indications of the existence of two independent discharge types – a diffusive and a filamentary ones, that spontaneously transit from one type to the other.
6. Formation of moving plasma balls and filaments

The formation of moving plasma balls (also called “bubbles” or “fireballs”) and filaments (figures 10, 11) in a SW produced plasma column has been first reported in [11]. The typical plasma parameters are as follows: plasma density of $1 \times 10^{11} \text{cm}^{-3}$, electron temperature of 1 eV, tangential SW electric field amplitude of 10 V/cm, absorbed microwave power varying from 10 to 100 W c.w. The contracted core transits in plasma balls and filaments, the latter evolving with increasing pressure to “strings of fireballs”. At lower pressure the fireballs are comparable in size to the column radius and they gently “swim” immersed in the background plasma (figure 10). When increasing pressure the size of the fireballs decreases to few millimeters, their movement becomes chaotic and one could even hear them bouncing the tube walls (figure 11). The behavior of the strings of fireballs is similar to that of the filaments, commented in Section 5, e.g. the splitting of a string into two strings (figure 12), but with increasing microwave power from 10 to 100 W c.w. may become more complicated, as for example, the cascade decay of strings of larger fireballs into strings of smaller ones (figure 13) or strings’ entanglement (figure 14). Dark and light halos surrounding the plasma balls, looking very much like the usual strata in the positive column of DC glow discharges could be seen on figures 10 and 13 – 15.

Figure 10. “Fireballs” (originally called “bubbles” [11] along a SW sustained plasma column (xenon, 100 mTorr, 42 mm i.d. tube)

Figure 11. Chaotic behaviour of strings of fireballs, tending to concentrate near the boundary (xenon, 1 Torr, 42 mm i.d. tube)

Figure 12. A string of fireballs split in two strings of fireballs (similar to figure 9) in xenon, 0.5 Torr, 42 mm i.d. tube.

Figure 13. Strings of fireballs cascading. Discharge conditions are as in figure 12.

Figure 14. String of fireballs entanglement. Discharge conditions are as in figure 12.

Figure 15. Strings of fireballs with light and dark halos surrounding the balls and the space between.
Moving fireballs have also been found to arise in an argon HF/microwave (27-400 MHz, input power 75 W c.w.) SW sustained discharge above a pressure limit of 350 mTorr and 1.5 Torr for 64 mm i.d. and 124 mm i.d. tubes, respectively [16].

7. Discussion and conclusions

With a single exception (the plasma rings discussed in Section 3) all other spatial structures could be considered to have similar nature and ordered in some scheme, as: i) the electromagnetic wave (not necessarily a surface one, or excited by a surfatron) creates one or more wave channels (contracted column, filaments); ii) in some situations each wave channel forms plasma balls and transits into a string of balls, some of them looking rather strange. The number of filaments increases while their size and the size of the fireballs (if present) decrease with increasing the neutral gas pressure. The transversal size of the filaments tends to decrease when increasing the wave frequency.

The physical mechanisms involved in the creation of these structures include ionization and heating instabilities, non-uniform neutral gas heating, connected with the electromagnetic wave skin effect, bifurcation phenomena due to step-wise ionization, plasma density profile modification due to ponderomotive effects of the surface wave and more (we could add here also the excitation of static electric fields and the appearance of the associated double layers). It seems, however, that the simple explanations on a fundamental/elementary level have been exhausted and the system should be studied in its complexity instead.

In conclusion, we have presented results of an experimental study on spatial structures appearing along a SW sustained plasma column at low to moderate pressure. The main conclusions of our study are summarized as follows. We have observed:

- static rings in xenon at low pressure and large diameter tube (single, or as set of several rings, azimuthally symmetric or obliquely oriented; both rings and the space between them show maximum light emission intensity near the plasma column periphery)
- standing-wave striation-like structures (plasma balls) similar to those observed in high frequency electrode and electrodeless discharges, these have been theoretically explained (with a convincing experimental support) as nonlinear/bifurcation phenomenon, severely dependent on whether the ionization rate is proportional to the electron density or its square; in our experiments the confinement by the tube seems to be important for the behavior observed
- plasma column contraction and splitting into filaments; both core and splitters may rotate slowly; this phenomenon has been observed also in previous studies on microwave discharges in noble gases
- appearance of plasma fireballs and filaments, transiting into strings of fireballs, as a result of an evolution of a contracted plasma core.

With some exceptions (the formation of standing-wave striation-like plasma balls), most of the complex phenomena observed still have not found their adequate theoretical explanation and the complete picture remains rather unclear.

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