Development of the microwave-surface-wave-sustained low-pressure discharge in standing wave field

V I Zhukov\textsuperscript{1,2}, D M Karfidov\textsuperscript{1}

\textsuperscript{1} Prokhorov General Physics Institute of the Russian Academy of Sciences, Moscow, Russia

\textsuperscript{2} E-mail: zhukov.vsevolod@physics.msu.ru

Abstract. Propagation of the low-pressure surface-wave-sustained microwave discharge becomes unstable in the final stage of the discharge development. The development of such instability is associated with the field perturbations in the region near the discharge front. The discharge development becomes stochastic that manifests itself in partial decays, jumps and stops of the front propagation. By means of setting the configuration of the field created by the discharge along its propagation path, it becomes possible to control the discharge development. The discharge propagation was studied in the standing wave field between two metal mirrors. It was found that between the mirrors, the discharge propagates irregularly in the form of successive plasma bunches with the $\lambda/2$ length.

1. Introduction

The low-pressure discharges in dielectric tubes sustained by the surface electromagnetic waves (SEWs) have been actively studied since the 1950s [1]. This discharge can be considered as a self-matched plasma waveguide created and supported by the SEW propagating along it. A distinctive feature of such discharges is the high electron density, which considerably exceeds the critical density for a given frequency [2]. The discharge front propagates from the microwave radiation source, leaving behind the plasma column, along which the SEW energy is transported to the discharge front [3]. The discharge front velocity decreases approximately exponentially along the tube length until the discharge propagation is terminated [3]. When the discharge propagation is not limited by the tube length, the instabilities can develop that are characterized by the partial decays, jumps, and stops of the front propagation. These instabilities are observed in the discharge tail in the final stage of the discharge development [4]. These effects most clearly manifest themselves under the optimal conditions of the discharge excitation, when the plasma column length considerably exceeds the wavelength. They have been observed both in air and argon and, apparently, do not depend on the gas type. The development of such instability is associated with microwave emission from the region near the discharge front and reflection of the surface wave from it. The installation of mirrors makes it possible to control the discharge propagation. In this case, the plasma column becomes the antenna irradiating the bulk wave. The reflection of this radiation from the conducting mirrors results in the formation of the standing-wave-type structure that determines further discharge propagation and its properties.

2. Experimental setup

Figure 1 shows the schematic of the experiment.
The discharge is initiated in quartz tube (4) with a length of 2 m, inner diameter of 21 mm and outer diameter of 27 mm. The tube was filled with air at a pressure of 0.1 Torr. The SEW is excited by surfaguide (2) [5] connected to magnetron (3). The magnetron with a power of 800 W operates at a frequency of 2.45 GHz. The magnetron generates single rectangular pulses with duration of 40 ms. The surface-wave-sustained discharge propagates along the tube from the surfaguide and forms the SEW-sustained plasma column between the surfaguide and the first mirror M1. To form the field structure in the tube, a system was designed similar to the open cavity. It consists of two flat copper mirrors M1 and M2 with the radii of 12 cm, through the centers of which the discharge tube passes. The first mirror is not in contact with the tube walls: the fluoroplastic bushing is installed in the one-centimeter gap between them.

Relative measurements of the electric field components are performed using the microwave probe. The cross-sectional distribution of the mean plasma density is measured using data on the intensity of the discharge glow detected by the collimated photodiode. It was shown in [6] that when the condition \( fR \geq 2 \text{ GHz} \cdot \text{cm} \) is satisfied \((R \) is the inner tube radius), the SEW dipolar \( m = 1 \) mode is excited in the plasma column. In the present experiment, the excitation of purely dipolar mode was confirmed by the measurements of the azimuthal field distribution. Absolute plasma densities were calculated using the dispersion relation for the dipolar mode [7], which relates the wavelength to the plasma density. The high-speed camera is used to record the discharge propagation.

### 3. Experimental results and discussion

Energy pumping was performed through the coupling aperture in the first mirror: the discharge plasma penetrates into the gap between the mirrors and becomes the coupling element that excites the standing wave field there. The interference of the bulk field with the field in the region near the discharge front leads to the formation of the local field minimum, in the vicinity of which the condition for the surface wave existence is violated [2]: \( n > n_{\text{min}} \; ; \; n_{\text{min}} = (1 + e_d) n_c \approx 3.8 \cdot 10^{11} \text{ cm}^{-3} \), where \( e_d \) is the dielectric permittivity of quartz, and the critical plasma density is \( n_c = 6.6 \cdot 10^{10} \text{ cm}^{-3} \).

In the vicinity of the standing-wave node, the discharge front velocity decreases to almost zero, or even the front completely stops. The plasma density distribution near the discharge front has a diffusive character and the electron density decreases from the region with the critical concentration \( n_{\text{min}} \) to zero over a characteristic length of 1–2 cm (Figures 2 and 3). Displacing the mirror, we can adjust the field distribution and thus, control the position of the discharge tail with respect to the standing wave field. When the avalanche frequency \( \tilde{\nu} = \nu_i - \nu_{\text{loss}} \) becomes zero \((\nu_i \) is the ionization rate and \( \nu_{\text{loss}} \) is the electron loss rate equal to \( \approx 10^{5} \text{ s}^{-1} \)), the discharge propagation stops (Figure 2) and it becomes stationary. Figure 3 corresponds to the positive avalanche constant: for a considerably long time \((30-300 \mu s) \) the discharge tail moves in the vicinity of the local field minimum.
Figure 2. (1) Electric field $E_n^2(z)$ and (2) plasma density $n_d(z)$ distributions at avalanche rate $\tilde{\nu} = 0$.

The plasma with such a density distribution at the discharge boundary falls into the region of the bulk field increasing towards the field antinode, which results in a considerable increase in the ionization rate. When the density exceeds $n_{min}$ the surface wave continues propagating. Such discharge development lasts till the wave reaches the next field node, where it stops, and then the entire process repeats. Thus, the discharge propagates in the form of successive plasma bunches with a length of $\approx \lambda_c/2$, where $\lambda_c \approx 10–11$ cm is the wavelength of the surface wave, until the reserves of energy are exhausted or until the discharge reaches the second mirror. The discharge front velocity distribution along the tube length has nonmonotonic jump-like character with the maximums in the field antinodes (Figure 4).

Figure 4. Discharge propagation velocity distribution along dielectric tube in the case of discharge propagating in the form of successive plasma bunches with a length of $\lambda_c/2$.

The ionization rate $v_i$ was determined from data on the rise time of the glow intensity. The ionization rates $v_i$ measured in the antinodes were in the range from $10^6$ to $5 \cdot 10^8$ s$^{-1}$. It can be seen that with the formation of each next bunch, the average velocity decreases in proportion to the drop in the ionization rate related to the front velocity $v_f$ by the relation $v_f = v_i \Delta f$ [3], where $\Delta f$ is the characteristic front width, which is constant along the tube and equal to $\approx 1.5$ cm. The stationary plasma column is formed in the final stage of the discharge propagation. The image of such a column, consisting of four bunches, is shown in Figure 5.

Figure 5. Image of the discharge after reaching the second mirror.

Adjusting the cavity, it was possible to form from one to six plasma bunches. The states corresponding to the maximum and minimum column lengths are spaced by distances of $\lambda_c/2$. When the discharge reaches the second mirror, the emission from the discharge tail region terminates, and only the surface wave exists between the mirrors.

Figure 6 shows the integrated plasma emission intensity $I(z)$ (curve 1) and the radial component of the SEW electric field $E_r^2(z)$ (curve 2) as functions of the coordinate directed along the plasma column.
Due to the partial SEW reflection from the plasma column boundary, the field distribution corresponding to the partial standing surface wave is formed along the column. The standing SEW wavelength $\lambda_c/2$ changes along the plasma column from 5.5 to 5 cm, while its wavelength in free space is $\lambda_0 = 12.1$ cm. It follows from the dispersion relation that such change in the wavelength $\lambda_c$ corresponds to a decrease in the density $n_e$ from $8 \times 10^{11}$ to $4 \times 10^{11}$ cm$^{-3}$. The Figure illustrates that the modulation of the SEW field corresponds to the modulation of the plasma emission intensity, which is proportional to the changes in the plasma density. Based on the condition for the SEW existence, we can state that even in the field nodes, the electron density is not lower than $n_{\text{min}} \approx 3.8 \times 10^{11}$ cm$^{-3}$.

Figure 7 shows the transverse distribution of the radial $E^2(z)$ and longitudinal $E^2(r)$ components of the electric field. The presence of the longitudinal component parallel to the direction of wave propagation is typical of only the surface waves. The measured $E^2(r)$ component exponentially decreases to zero over a length of 5 cm that is in good agreement with the theory [6]. Both the surface and bulk waves contribute to the distributions of the transverse component $E^2(r)$. At distances less than 3 cm, the surface wave field prevails and the law of transverse component damping qualitatively coincides with that for the longitudinal component. At distances exceeding 3 cm, the cavity volume field prevails.

4. Conclusions

Thus, it is shown that the strict setting of the field structure makes it possible to control the character of the discharge propagation. It is found that in the standing wave field, the discharge propagates in a jump-like manner in the form of plasma bunches with a length of $\lambda_c/2$, followed by the formation of the stationary plasma column sustained by the surface electromagnetic wave.

Funding

This work was funded by the Russian Foundation for Basic Research, project no. 20-32-90162.

References

[1] Trivelpiece A W and Gould R W 1959 J. Appl. Phys. 30 1784
[2] Trivelpiece A W 1958 Slow wave propagation in plasma waveguides, PhD thesis (California Institute of Technology, Pasadena)
[3] Zhukov V I, Karfidov D M and Sergeichev K F 2020 Plasma Phys. Rep. 46 837
[4] Zhukov V I, Karfidov D M and Sergeichev K F 2019 J. Phys.: Conf. Ser. 1383 012021
[5] Moisan M, Shivarova A and Trivelpiece A W 1982 Plasma Phys. 24 1331
[6] Matgot-Chaker J, Moisan M, Glaude V M, Lauque P, Parasyczak and Sauve G 1989 J. Appl. Phys. 66 4134
[7] Zhelyazkov I and Atanassov V 1995 Phys. Rep. 255 79